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Modeling of ray paths of head waves on irregular interfaces in TOFD inspection for NDE

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20

21 **Abstract:**

22 The TOFD (Time Of Flight Diffraction) technique is a classical ultrasonic inspection method
23 used in ultrasonic non-destructive evaluation (NDE). This inspection technique is based on an
24 arrangement of two probes of opposite beam directions and allows a precise positioning and a
25 quantitative evaluation of the size of cracks contained in the inspected material thanks to their
26 edges diffraction echoes. Among the typical phenomena arising for such an arrangement,
27 head waves, which propagate along the specimen surface and are chronologically the first
28 waves reaching the receiver, are notably observed. Head wave propagation on planar surfaces
29 in TOFD configurations is well known. However, realistic inspection configurations often
30 involve components with irregular surfaces, like steel excavated specimens.
31 Surface irregularity is responsible for numerous effects on the scattering of bulk waves,
32 causing the melting of surface and bulk mechanisms in the head wave propagation. In order to
33 extend the classical ray approach on these complex cases, a generic algorithm of ray tracing
34 between interface points (GIRT) has been designed. With respect to time of flight
35 minimization (i.e. the generalized Fermat's principle), ray paths can be computed by GIRT
36 for different natures of waves scattered by the complex surfaces or by flaws. The head wave
37 fronts computed by GIRT are notably in good agreement with FEM simulated results. This
38 algorithm, based on pure kinematic analysis of waves propagation, represents a first step in
39 the future development of a complete ray theory for head waves simulation on irregular
40 interfaces.

41

42 **Keywords:**

43 head wave, ray tracing algorithm, irregular surface, wave diffraction, non-destructive
44 evaluation

45

46 **1. Introduction**

47

48 Head waves are well known phenomena occurring in seismic inspections: they correspond
49 to the first wave received by seismic probes, giving so their names. Typical seismic
50 inspections deal with configurations involving two media separated by a planar interface.
51 Specific wave theories have been developed, all considering head waves on planar surfaces as
52 critically refracted waves. These modeling approaches are based on an asymptotic integral
53 evaluation [1], the asymptotic ray theory [2,3] or the generalized ray theory (Cagniard-De
54 Hoop method) [4,5]. It is shown that the head wave on planar interfaces corresponds to the
55 combination of both waves travelling along one interface side with the corresponding material
56 sound velocity (compulsory more than that of the incident wave), and bulk waves radiated
57 from the interface towards one material and propagating at the critical angle. The waves
58 propagating along the interface are composed of the well-known lateral waves [1–6] and of
59 the Goodier-Bishop type waves [7] for the case of a finite beam impacting the interface.

60 Head waves on planar surfaces are also observed in NDE by using specific techniques and
61 similar configurations than the seismic ones. Among the various NDE inspections techniques,
62 the Time of Flight Diffraction (TOFD) technique allows a precise and quantitative evaluation
63 of surface breaking or embedded cracks. This technique uses two probes moving on the
64 inspected material surface with a fixed Probe Center Spacing (PCS). The TOFD configuration
65 is particularly well adapted to generate and receive head wave signals [8–10] (sometimes used
66 for surface breaking cracks detection).

67 The CIVA software platform for NDE simulation, developed at CEA/LIST, enables a
68 complete simulation of TOFD inspections: indeed different semi-analytical models [8,11,12]
69 have been integrated to model all the echoes observed in a TOFD configuration (head wave,

70 flaw edges diffractions, back wall echo...). The developed model for head waves simulation
71 is based on the asymptotic ray theory [3] which has also been used to improve the modeling
72 of flaw corner echoes [13,14]. Nevertheless, the existing head wave simulation can only be
73 applied for a planar specimen composed of an isotropic medium.

74 TOFD and other pitch-catch configurations are also classically used on non-planar
75 interfaces both in NDE (inspections of cylinders, nozzles [8]..) and in the seismic domain:
76 indeed in works carried out by Zhou and Chen [15], head wave travel times have been
77 calculated by numerical simulations on some irregular surfaces for some seismic inspections.
78 It has been shown that the head wave propagation is more complex on irregular surfaces than
79 on planar surfaces. Indeed, whereas the head wave on a planar interface is due to the critical
80 refraction of the incident wave and includes a surface wave component propagating along the
81 planar surface (called lateral wave), the head wave propagation on irregular surfaces implies
82 propagations in the material bulk. The received head wave signal on irregular surfaces has a
83 different amplitude than in the planar case and a travel time compatible with the hypothesis of
84 propagation in the material bulk. Analytical modelings of the head wave propagation around
85 the Earth have also been proposed in several seismic studies. Indeed, using an integral
86 representation of the solution, the received head wave signal has been evaluated for slightly
87 curved irregularities [16,17] of surface parametric equation $F(x) = x^2 / 2D$ with large values of
88 the radius of curvature D compared to the surface size, and for spherically symmetric radially
89 heterogeneous media [18]. These studies confirms conclusions given in [15] concerning the
90 time of flight and the amplitude of the head wave.

91 In the present study, complete interpretation and simulation of the head wave propagation
92 mechanisms for irregular surfaces are proposed. This approach leads to the development of a
93 generic algorithm of ray tracing between interface points (called in the following for
94 simplification Generic Interface Ray Tracing/GIRT) which is able to compute the travelling

path of head waves in specimens inspected by TOFD technique. Based on an adaptation to the NDE domain of seismic ray tracing algorithms, GIRT is a new method for solving the two-points ray tracing problem, which is the calculation of the true ray between two defined points: the source and observation points.

Ray-tracing techniques are often employed for modeling wave propagation in electromagnetism, optics, seismology ... Traditional ray tracing algorithms are the shooting method [19] and the bending method [20,21]. The shooting method, well adapted for field propagation modeling, fixes the source point, takes initial ray direction and then finds the location of the observation point; in the view of two-points rays tracing, an iterative procedure for finding the starting direction can be used to yield the desired observation point. Ray bending is a variational approach which perturbs some initial estimate of the ray path, the ends being fixed, until the true ray which minimizes the travel time is found. The two previous traditional methods are heavy in time computation for solving the two-points ray tracing problem and not efficiently adapted to deal with diffracted waves and shadow areas in which head waves around irregular surfaces propagate.

To improve efficiency of the shooting method on the diffracted waves calculation, seismic ray tracing algorithms based on a grid based scheme were developed more recently : wave front construction [22], the finite difference Eikonal equation solver [23–27] which also

generally needs large computation time for tracing rays and Shortest Path Method (SPM) algorithms [28–35] (also called minimum travel time tree - MTTT) which are relatively underdeveloped algorithms based on Huygens' and Fermat's principles. Compared with the traditional ray tracing algorithms, the grid based scheme has several advantages for

application to NDE modeling: it is able to easily locate ray paths in shadow zones; it is numerically stable and can find the first arrival in complex media.

The current study proposes, for modeling the propagation of an incident beam towards a receiving probe in a specimen of irregular surfaces including flaws, an approach based on seismic SPM algorithms adapted to ultrasonic NDE and specifically designed for the two points ray tracing problem. For a 2D propagation, the initial SPM Moser's algorithm [29] consists in launching rays from a source, in considering in a 2D grid the adjacent node with minimal travel time as a secondary source, in repeating the previous process so as to propagate first arrival waves to the 2D grid nodes. More recently, Zhang et al [35] developed the interface source method (ISM): as in Moser's SPM, first arrival waves still propagate using a ray shooting scheme from nodes to nodes in a 2D grid but on the other hand only interface points are taken as secondary sources. The developed GIRT model uses a new SPM approach specifically devoted to two points ray tracing in a propagation medium constituted of homogeneous volumes (in terms of sound velocity). The GIRT takes advantages that in the latter case waves propagate in straight lines between interface points: only the specimen interfaces are meshed (in a simple 1D mesh for a 2D propagation), the source (on the emitter) and observation (on the receiver) points are added to the mesh and the wave ray path of minimum travel time passing through mesh points is found between the two fixed points. One of the major advantages of this GIRT method is the fast processing of very irregular surfaces as only the surfaces of the specimen are meshed and not all the specimen volume like in other SPM algorithms [28–35]. In addition, GIRT directly traces in an optimized manner (a two points ray tracing) the shortest path from a source reaching any required observation point located anywhere (outside the 2D grids needed by previous methods to propagate all shortest paths to all grid nodes).

Furthermore, compared to the ISM method [35], the developed GIRT algorithm has notably added features to meet the specificities of ultrasonic NDT applications. Firstly, whereas ISM has been shown to deal with only the first arrival or one reflection path for P bulk waves, the GIRT algorithm is adapted to find not only the head wave ray path (first arrival) but also all complex later arrival waves including mode or nature conversion by adding constraints on the searched ray path, fixing one or more points through which the ray path must pass, and by defining independent types of wave propagation along each path connecting the constraint points. Secondly, the GIRT can take into account all types and natures of waves propagation occurring in NDE. Indeed the propagation is available not only for the SH head waves studied in [15] (also called TH) but also for P and SV waves (also called L and TV). Surface waves as Rayleigh waves and head waves are taken into account as well as diffractions from surfaces in any kind of waves. Finally, GIRT approach is extended to flaw scattering modeling since the flaws contained in the specimen are also meshed by the GIRT algorithm in order to model rays diffracted from flaws. Consequently the GIRT algorithm is generic for application to NDE as it can deal with any ultrasonic wave propagating near irregular surfaces or flaws of any geometry (CAD defined). Finally this tool is able to calculate valid geometric ray paths after interaction with interfaces or flaws. One interest of the study presented in this paper is also to evaluate the applicability of such a method initially based on seismic ray tracing in NDE applications for which the characteristic dimensions (propagation distance or scatterer size) to the wave length ratio can be smaller than in geophysics. The current study shows that GIRT leads to a better understanding of the head wave propagation and its interaction with the surfaces. In that aim, a data fusion of simulated results obtained by both GIRT and a FEM-based method is carried out.

The paper is organized as follows. The theoretical principles of the approach, the GIRT algorithm process and the GIRT capabilities are described in section 2; some ray tracings and

wave fronts of the head wave and some later arrival waves, simulated with GIRT in 2D applications, are compared for validation with FEM results in section 3.

2. The Generic Interface Ray Tracing (GIRT) method

The development of a ray tracing method allows a better understanding of the head wave propagation on irregular surfaces by providing valid ray paths. The interest of such a study is described in parts 2.1 and 2.2. The developed ray tracing method (GIRT) is generic by the fact that it supports any kind of wave propagation and interaction with an irregular surface, and describes the physical phenomena involved in the head wave propagation. Its theoretical principles, functionalities and operating process are detailed in part 2.3.

2.1. Head waves in planar surfaces configurations

For a planar surface inspected in TOFD, a head wave is generated at the interface between the material and the emitter and propagates in the material along the surface, and is radiated as a bulk wave in the wedge, reaching the receiver. For planar surfaces, the head wave is seen as the result of a critical refraction phenomenon of the incident wave on the interface between the two media. *Fig. 1* describes, in a TOFD inspection of a planar specimen containing an embedded crack, the propagation of different waves including the head wave.

Fig. 2 illustrates the B-scan measured in the inspection described in *Fig. 1*. Three kinds of signals can be observed and are characteristics of a TOFD inspection on a planar specimen. These signals correspond respectively to the head wave (1), the diffraction (2, 2') of the refracted bulk wave on the edges of the crack and the reflection (4) of the refracted bulk wave on the specimen bottom.

2.2. Head wave in irregular surfaces configurations

TOFD inspections of specimen with irregular entry surfaces can be required for specific NDE applications. For example, the process of repairing a material including a surface breaking crack implies to remove the matter around the defect then to replace the removed matter. The TOFD technique is applied on the specimen between the two reparation stages in order to ensure that the entire defect has been removed. The geometry of the specimen after matter removing is presented in *Fig. 3*.

A good understanding of the head wave propagation on such surfaces is essential for the complete modeling of TOFD inspections on realistic configurations. In particular, the head wave signal is one of the main references for the detection and the location of potential defects in the specimen. As explained in [15], irregularities of the specimen surface induce modifications on the head wave received signal compared to that observed on planar interfaces. Indeed such modifications can be noticed on experiments: the B-scan presented in *Fig. 4* is extracted from a TOFD inspection measurement on the specimen described in *Fig. 3* and highlights two kinds of differences which can be observed when scanning over the surface irregularities. Firstly, the head wave time of flight appears to be incoherent with the hypothesis of head wave propagation all along the entry surface: indeed the measured travel time is less than that of a surface wave propagating all along the complex surface. Secondly, the irregular surface causes an important decrease (more than 15dB) of the head wave amplitude compared to a planar interface.

To understand the physical process responsible for the observed head wave propagation on complex surfaces, an analysis of the nature of the field propagating near such surfaces has been carried out: the emitter generates a refracted field in the material which interacts with the

surface. In particular, surface corners are responsible for diffracting the field in their geometrical shadow. Thus head wave propagation cannot be considered as a critical refraction anymore like in the case of planar surfaces, but the result of the diffractions of the generated refracted field on the surface irregularities. *Fig 5a* describes such behavior on an example of irregular surface: the head wave, after a bulk refraction of the incident wave, is diffracted two times on the surface corners, in order to create a diffracted wave, which is then refracted again towards the receiver. In order to visualize this behavior, some numerical simulations have been carried out with the hybrid technique CIVA/ATHENA [36] using both analytical models and finite elements simulations near the surface irregularities. The principle of this technique is the following. A volume in the specimen is defined, embedding the surface and its irregularities. The field reaching the volume entry is calculated by the analytical CIVA pencil method on the volume border. Then the field is propagated in the defined volume by the finite elements scheme ATHENA. The results of this simulation are presented in *Fig. 5b* and show that there exists a field diffracted from the surface corner in the geometrical shadow area of the irregular surface: the corresponding diffracted rays will generate the head wave (*Fig 5a*).

2.3. GIRT objectives and principles: construction of valid ray paths

Considering the behavior of the head wave near an irregular surface, the ray theory formalism is then applied for the two points ray tracing problem. The head wave propagation and more generally all the waves in the specimen are then the result of specific interactions between the wave field inside or outside the specimen and the specimen surface: the ray path representing this propagation is the combination of specific rays connected to each other by secondary source points. These secondary source points are located on the specimen surface

and correspond to the locus of each interaction responsible of the wave propagation. The rays are a representation of the wave propagation between each secondary source points.

The GIRT ray tracing formalism is thus based on the Huygens principle. Considering known source point M_s and observation point M_o , there exists a secondary source points collection $\{M_i\}_{i \in (1, \dots, N)}$ located on the specimen/flaws surfaces which represents the locus of all potential interactions between the wave field and the surfaces: the size N of the secondary source points increases with the complexity of the surface irregularities. The ray path associated to a wave propagation between the points M_s and M_o is then a combination of elementary particular rays $(M_j M_l)_{(j,l) \in (s,o,1, \dots, N)^2}$ whose extremities are secondary source points M_i among the collection $\{M_i\}_{i \in (1, \dots, N)}$ of an elementary ray emitted from M_s and of an elementary received on M_o .

In the following, it is illustrated on examples (*Fig. 6*) that this principle of secondary sources can be applied to represent all physical waves in a propagation medium containing interfaces and flaws. In a general manner, numerous waves including the head wave are emitted from a source point M_s and received on an observation point M_o : these waves are characterized by their interactions with the specimen surfaces involved in their propagation and then by the secondary source points constructing the associated ray path. Moreover, these interactions may be responsible of a wave mode or wave nature conversion:

consequently, each elementary ray $(M_j M_l)_{(j,l) \in (s,o,1, \dots, N)^2}$ can represent the propagation of a longitudinal (L) bulk wave, transversal bulk waves (T in an isotropic medium, qT1 and qT2 in anisotropic one), lateral surface wave (L or T) or Rayleigh-like (Rayleigh, Generalized Rayleigh, Stoneley) wave depending on the type of interaction located on the secondary source point M_j which is the departure point of ray $(M_j M_l)_{(j,l) \in (s,o,1, \dots, N)^2}$.

Two inspection configurations involving irregular surfaces are studied as examples in *Fig. 6*. The first configuration (*Fig. 6a*) is a three propagation media one for inspection of a specimen including a corner irregularity on its entry surface, an internal interface with slopes and a defect. The case of an isotropic elastic specimen with an entry cylindrical surface is shown in *Fig. 6b*. The upper medium is a fluid one in both cases. Each ray path in *Fig. 6a* and *Fig. 6b* represents one particular wave propagating. Only some ray paths among all existing are shown as examples and the secondary source collection $\{M_i\}_{i \in (1, \dots, N)}$ is consequently not exhaustive.

As to the configuration of *Fig. 6a*, the ray path $M_s M_2 M_5 M_{12} M_o$ (path 1) is the ray with the shortest time of flight and thus corresponds to the head wave propagation: its path is composed of a refraction at M_2 of the longitudinal bulk wave emitted at M_s , a corner diffraction at M_4 without mode or nature conversion and a refraction towards the observation point M_o . However the diffraction of the L bulk wave at the corner M_5 implies also a mode conversion into a T wave and gives after refraction at M_{11} the ray path $M_s M_2 M_5 M_{11} M_o$ (path 2 in *Fig. 6a*) with a higher time of flight than the head wave ray path. The ray path $M_s M_3 M_4 M_5 M_7 M_{10} M_o$ (path 3) is associated to a L bulk wave critically refracted at M_3 into a L lateral wave which propagates along the surface and is critically reradiated at M_{10} into a bulk L wave. As another example the secondary source point M_7 also converts the lateral wave into a Rayleigh wave which radiates at M_9 a bulk L wave and gives the ray path $M_s M_3 M_4 M_5 M_7 M_9 M_o$ (path 4). Finally the ray path $M_s M_1 M_6 M_8 M_{13} M_o$ (path 5) corresponds to a L bulk wave emitted at M_s and refracted at M_1 which is reflected on the internal interface of the specimen on M_6 and diffracted on the edge defect on M_8 before reaching M_o .

Fig. 6b shows the ray paths of different waves which propagate close to a surface with a cylindrical irregularity. The head wave propagation is associated to the shortest ray path $M_s M_1 M_4 M_5 M_9 M_o$ (path 1): the emitted L bulk wave is refracted in the specimen at M_1 and diffracted on the cylindrical irregularity in a surface creeping ray $M_4 M_5$; the wave propagates along the irregularity and is then radiated again at M_5 , and refracted at M_9 towards the observation point M_o . Similarly to the path 3 of *Fig. 6a* along the corner irregularity, the ray path 2 ($M_s M_2 M_3 M_6 M_8 M_o$) represents the L lateral wave propagation along the cylindrical irregularity generated by a critical refraction at M_2 and the critical radiation at M_8 . A Rayleigh wave is also created at M_6 which radiates at M_7 and give the path 3 $M_s M_2 M_3 M_6 M_7 M_o$.

Ray paths not shown on *Fig. 6a* and *Fig. 6b* result from other interactions in the specimen. For example, mode conversion of the emitted L bulk wave occurs at the refraction on the entry surface, at specular reflections or at diffractions on the specimen surface irregularities or flaws (like at M_8 in *Fig. 6a*) and allows the propagation of several transversal bulk waves into the specimens. Mode conversions of bulk waves into Rayleigh-like waves also occurs on surface irregularities (at M_4 , M_5 , ... in *Fig. 6a* or M_3 in *Fig. 6b*).

Finally the purpose of the GIRT is to find all physical paths described above in isotropic or anisotropic media using the Generalized Fermat's Principle. This principle is a basic one of an asymptotic ray theory, the Geometrical Theory of Diffraction (GTD) [37] which extends Geometrical Acoustics by adding rays diffracted from canonical scatterers (edges, corners, curved smooth objects...) to the classical geometrical (refracted and reflected) rays. In the aim of ray tracing, the Generalized Fermat's Principle allows to determine if a ray path represents a physical wave propagation and is consequently valid. Indeed this principle indicates that the valid ray path for a wave resulting from particular interactions between the

wave field and surfaces and is the one providing the stationary time of flight and respecting the predefined conditions imposed to the wave propagation (choice of the modes for instance). This principle is verified by finding the minimal time of flight and the associated ray path. Consequently the principle of the GIRT is to find the valid ray path respecting the Generalized Fermat's principle and achieving the wave propagation conditions using a time of flight minimization technique. Its algorithm process is described in the following section.

2.4. GIRT algorithm process

The steps of GIRT algorithm process are described in this section for the general case of anisotropic media and schematically represented in the functional diagram of *Fig. 7*. This algorithm process is the subject of a patent filing [38].

This process is first described when used for determination of the head wave path, the first arrival (like the paths 1 on *Fig. 6a* and *Fig. 6b*) and is called in that case GIRT-A. The input data (step 1) of the GIRT are the CAO description of the specimen in which the ray path has to be calculated, the source and observation points which are the ray extremity points, the slowness surfaces for the wave propagation mode desired inside and outside the specimen, the description of defects inside the specimen and the discretization fineness of the specimen or flaw surfaces which defines the calculation accuracy.

Indeed the next steps of the algorithm process is the discretization of both each specimen surface (step 2) and of each existing defect (step 3) in order to deal with any irregular surface: for the configuration of *Fig. 6a*, the two irregular surfaces and the planar defect are meshed.

The obtained discretization points collection $\{M_i\}_{i \in (1, \dots, N)}$ constitutes the secondary sources collection for waves diffraction as stated by the Huygens principle in a propagation medium constituted of homogeneous volumes. Consequently these secondary sources are possible M_i

points composing the ray path as described in section 2.3. The GIRT at this step 2 uses a similar approach to the interface source method (ISM) developed by Zhang and al [35] since interface points are seen as secondary sources.. On the other hand, the discretization carried out by GIRT differs from that performed by ISM [35] and other SPM algorithms [29]. Indeed as only the surfaces and the defects are discretized, the ray path searching is done only through secondary sources located along the specimen and defects surfaces and not through a grid covering all the specimen volume. The obtained secondary sources collection has a limited size N compared to that generated from a volume discretization and provide a more stable and faster research of ray paths.

To determine the valid secondary sources involved in the searched ray path in the view of the two points ray tracing problem, the elementary paths between two secondary sources are calculated (step 4): an elementary path represents the wave propagation along a direct path involving two and only two M_i secondary sources without any other diffraction effect. All the valid elementary paths between two M_i points respecting the previous condition are calculated for all the M_i points and the associated elementary times of flight are deducted from the slowness surfaces given and stored by the algorithm process (step 5). As an example, the ray M_2M_5 in *Fig. 6b* is an elementary ray path of the path 1 and path 2.

A secondary sources collection, an elementary paths collection and an associated elementary times of flight collection have been obtained during the previous steps. The M_s source and M_o observation points are added in step 6 to the existing secondary sources collection and all the new valid elementary paths involving one of these two points are calculated and taken into account in the collections. The interest of having separated this step 6 from step 5 is to allow the ray path calculation for different couples of source and observation points but with the same specimen without needing to recalculate at each ray

calculation all the other elementary paths in the specimen (already independently determined at step 5).

Finally, knowing the secondary sources collection and the elementary paths collection, the search for the valid wave ray path in the view of the two point ray tracing reduces to an optimization problem. It indeed corresponds to the determination of which secondary sources M_i are involved in the ray path and then which elementary rays $(M_j M_l)_{(j,l) \in (1,\dots,N)^2}$ compose the ray path associated to the minimal time of flight. This approach is called the Shortest Path Method (SPM) [29] in the seismic domain and is applied in the GIRT (step 7). The secondary source points collection are the nodes of an oriented graph. In this graph, two different vertices are connected by an elementary ray path included in the collection. At each path is associated a cost which is the elementary time of flight between of the path. Once the graph is obtained, the optimal route (leading to the shortest time of flight between the source and observation points) is obtained by the classical Dijkstra algorithm [39], which has the major advantage to be a fast route search algorithm since all possible routes are not calculated: only the most likely optimal routes are taken into account. At that step, the GIRT algorithm differs strongly from the ISM developed by Zhang and al [35]. ISM is conceived to perform ray shooting in a grid meshing all the volume by launching rays from a source in all directions and by propagating first arrival waves from nodes to nodes in the grid: consequently a ray path reaching a predefined observation point cannot be found directly notably if this point is not a grid node. In GIRT, the application of the Dijkstra algorithm on the secondary sources collection is well fitted and specific of the two point ray tracing problem. Indeed, the source and observation points have been integrated in the secondary sources collection so that the fast route search gives directly the valid ray path between these two points.

Later arrival waves (for example all paths represented in *Fig. 6a* and *Fig. 6b* except the paths 1) can also be modeled by a GIRT-B version by adding constraints on the searched ray

path, fixing one or more points through which the ray path must pass. In the case of a ray path calculation with obligatory points of passage, the GIRT-B process differs from that previously described for the head wave ray path (GIRT-A process) only by some slight changes. First, the GIRT-B inputs include in addition the list of sorted constraint points and the definition of independent types of wave propagation along each path connecting these points. Then the GIRT-B operates as follows: a couple of points is formed by the source point and the first constraint point, then several other couples by two adjacent constraint points and the last couple by the last constraint point and the observation point. An optimized ray is then searched between the two points of each couple: in that aim, the previous points are seen as the source and observation points for GIRT-A process and the GIRT-A process is consequently carried out independently for each couple, the latter having its own type of propagation, allowing all type of wave propagation in the specimen. At last, all the calculated couples ray paths are concatenated to obtain the complete ray path between the source and observation points.

2.5. GIRT capabilities

GIRT is thus a generic algorithm calculating geometrical paths and the corresponding ray time of flight propagating in isotropic or anisotropic media. It has been designed to determine the valid ray path between two points assuming one or several given interactions between the current ray and the irregular surface. The two points can be located anywhere inside or outside the specimen.

Two kinds of interactions, accounted by GTD [37], are supported by GIRT: diffraction on smooth objects, leading to surface creeping rays (see the ray M_5M_6 on *Fig. 6b*), and diffraction on wedges or edges (see *Fig. 6a*), leading to bulk or surface diffracted rays.

Furthermore, the propagation of numerous wave modes is taken into account with potential mode conversion at the surface: the longitudinal and transversal modes (possibly occurring for different kinds of waves: bulk waves, lateral waves, reradiated head waves or surface waves...), and the surface Rayleigh-like waves.

All the ray paths presented on *Fig. 6a* and *Fig. 6b* are modeled by setting some wave propagation conditions supported by the GIRT. As an example the head wave ray paths 1 of *Fig. 6a* and *Fig. 6b* are calculated using by finding the shortest ray path for a longitudinal bulk wave without mode conversion. The ray path 2 of *Fig. 6a* is found for the condition of a wave propagation with the shortest time of flight and a mode conversion from L bulk to T bulk on the surface irregularity. The ray path 3 of *Fig. 6a* and the ray path 2 of *Fig. 6b* are modeled imposing a surface propagation condition (detailed in the comments of *Fig. 14*) to the ray path in order to propagate lateral waves along the specimen surface. Similarly the ray path 4 of *Fig. 6a* and ray path 3 of *Fig. 6b* are found using the same surface propagation condition and that of a wave mode conversion from a lateral wave to a Rayleigh wave. Finally the ray path 5 of *Fig. 6a* is calculated using a reflection condition on the internal surface and an obligatory point of passage M_8 on the defect edge.

Thanks to the previously described capabilities, all the interactions occurring in the case of an irregular surface and presented in this section are modeled by GIRT. In next Part 3 of this paper, GIRT is applied to the head wave path modeling in TOFD near irregular surfaces and only the waves which may be responsible of the head wave propagation or examples of the least later arrival waves are studied. It is shown in Part 3 that GIRT provides accurate predictions for the time of flight and wave fronts of both the head wave and even later propagation waves in TOFD near irregular surfaces.

3. GIRT simulated results and theoretical validations

Calculations using GIRT of ray paths and wave fronts are shown in this section in the aim of modeling the propagation of head waves near irregular surfaces in some TOFD configurations. Such simulations are compared and superimposed to FEM ones.

3.1. Validation of the head wave time of flight

A theoretical validation of GIRT is performed by comparing times of flight calculated with both GIRT and finite-elements (FEM) simulations obtained with CIVA/Athena, which is considered here as a reference model. The comparison deals with TOFD inspection simulations for several inspection directions ($\theta = 45^\circ$, 60° and 75° where θ is the angle defined in *Fig. 8*) with L waves emitted at 5MHz. The specimen is a planar stainless steel block which is inspected using two contact planar rectangular transducers (6mm*5mm). The specimen entry surface has two slopes. The head wave path determined by GIRT is illustrated in blue in *Fig. 8* and includes a diffraction on the surface corner.

The times of flight obtained by GIRT have been compared to the results of the FEM simulation software for different slope angles and are shown in *Fig. 9*. Each graph of the *Fig. 9* is associated to a particular inspection direction (from $L45^\circ$ to $L75^\circ$), the solid lines are the results obtained with the GIRT and the dashed lines are the results obtained by FEM simulations.

The graphs show a very good concordance between the results of the GIRT and FEM simulation, for each direction of inspection and any slope angle. The GIRT is then able to calculate the head wave time of flight with a very good precision (error less than 0.1%). The simulated times of flight of the head wave signal received by the probe are almost

independent of the inspection directions because the head wave signal is generated by only some refracted rays included in the beam radiated in the specimen by the emitter surface, those rays being close to the mean head wave path shown in blue in *Fig. 8* including a diffraction on the corner.

3.2. Analysis of the propagation of waves in the surface shadow

Additional finite-element simulations on CIVA/Athena have been performed on irregular surfaces including curved parts, and the propagation wave field in the material at different times is also visualized on FEM snapshots. In this section, GIRT has been employed in the aim of identifying the nature of waves propagation corresponding to some observed wavefronts in the FEM snapshots.

Indeed, when studying the interaction on a beam with an irregular surface, numerous wave fronts are generated. For instance *Fig. 10* shows FEM simulation of the waves propagation near a curved valley constituted of two curved edges separated by a planar part. Numerous wave fronts are observed in the FEM snapshot of *Fig. 10*, which highlights the great number of interactions occurring between the refracted field and the specimen. The nature of some of these wave fronts (numerated in *Fig. 10*) can be easily guessed. The surrounded front L1 corresponds to the direct L-wave refracted in the specimen by the emitter. The front L1 is reflected by the specimen bottom (dashed black horizontal line in *Fig. 10*) creating the L-wave front L2 and T-wave front T1. T2 refers to T-waves refracted in the specimen. Other wave fronts are of more complex nature. It is consequently of interest to identify the nature of rays which have generated the observed wave fronts in the FEM simulations.

So as to identify the nature of one particular FEM wave front, the following methodology is chosen:

- The studied wave front is identified on the FEM snapshot as the local maximum of the displacement field.
- An appropriate hypothesis on the wave propagation and interactions with the surface is formulated by the GIRT user to explain the generation of the studied wave front. Considering the previously chosen path hypothesis, GIRT builds rays until their time of flight reach the FEM snapshot time.
- The resulting wave front simulated by GIRT is then drawn for the FEM snapshot time by tracing the curve orthogonal to every ray found at this time of flight [40]. The GIRT simulated wave front is superimposed to the FEM snapshot and its location compared to that of the FEM studied wave front to validate the chosen propagation hypothesis.

In the present study, identification of wave fronts nature by comparing FEM and GIRT simulations is done only for wave fronts relevant for studying head waves propagation. But a similar analysis could be performed for all the other wave fronts observed on FEM snapshots. The method is thus applied for the following wave fronts:

- The front of the refracted L-wave (*Fig. 10*), whose diffraction on the second curved part of the surface specimen is responsible of head wave propagation towards the receiver (as said in section 2.2).
- The L head wave (*Fig. 11 and 13*), received at first on the receiver.
- The T wave received just after the L head wave on the receiver.

For each figure, the ray paths (white lines) and the front (dashed black line) simulated by GIRT are superimposed to the studied FEM snapshot (in color code).

In *Fig. 10*, ray paths simulated by GIRT are obtained considering the hypothesis injected in GIRT of a diffraction of the refracted L-wave field on a curved object without mode conversion and without constraint point. Ray paths are thus built with the GIRT-A algorithm between one source point (emitter center) and a set of observation points located in the

specimen bulk after the second curved part at right, inside the shadow areas formed by the surface irregularity. The GIRT objective is here to determine between the source and each observation point the shortest path which corresponds to the head wave path. The calculated ray path indicates that the emitted wave is refracted in the specimen bulk, before being diffracted by the first curved object at left. The GIRT modeling of the diffracted field by near this curved part reveals creeping rays. Indeed, the refracted longitudinal rays reaching tangentially the first curved object are converted into creeping rays. These creeping rays are then diffracted into both bulk rays along their curved propagation and a surface ray which propagates along the planar surface. The surface ray is converted again at the junction with the second curved part into a creeping ray which is diffracted into bulk rays generated tangentially to the second curved object at right inside the shadow area caused by the surface irregularity. As seen in *Fig. 10*, the calculated wave front is the result of the wave diffractions on the two curved objects. The previously described head wave propagation is validated by comparing the GIRT and FEM simulated wave fronts and observing a good agreement between them.

The following two cases, presented in *Fig 11* and *Fig 12* are obtained with the same configuration as in *Fig. 10*, but the propagation of waves is extended up to the receiver, allowing observing the wave fronts received in experimental studies. As in *Fig. 10*, the refracted longitudinal wave is diffracted by the curved parts at left and at right and refracted again at the last surface between the specimen and the wedge of the receiving probe. Two different hypotheses detailed hereafter are inputted in GIRT concerning the second refraction (at the interface specimen/wedge of the receiver) and give the results of respective *Fig. 11* and *Fig. 12*. In *Fig. 11*, a second refraction of longitudinal waves without mode conversion is assumed and GIRT-A is used to calculate the shortest rays between the source and observation points located on the receiver crystal surface. In *Fig. 12*, a second refraction with conversion

of the L wave into a T wave is supposed. To apply the last hypothesis, a constraint point is defined on the plane part of the irregularity and the GIRT-B algorithm is used so as to calculate the rays using the following assumptions: when the path takes place inside the specimen, it is always travelled at the celerity of the L wave; when the path takes place both outside the specimen and from the source point to the constraint point (i.e. in the emitter wedge), it is travelled at the celerity of the L wave; when the path takes place both outside the specimen and from the constraint point to the receiver point (i.e. in the receiver wedge), it is travelled at the celerity of the T wave. By this way ray paths calculated by the GIRT-B satisfy the mode conversion L-T condition on the surface near the receiver. As in *Fig. 10* and for the two cases in *Fig. 11* and *Fig. 12*, wave fronts calculated by GIRT perfectly match with two different wave fronts simulated by FEM. Furthermore the wave of type T (*Fig. 12*) is received by the receiver later than that of type L (*Fig. 11*) as shown by comparing the location of their corresponding wave fronts for a fixed time of flight. Consequently, in the previous configuration, the head wave observed at the receiver which is by definition the first received wave logically mainly corresponds to a complete path without mode conversion involving only faster L waves. All the other FEM simulated wave fronts obtained in the snapshot of *Fig. 11* lead to later arrival times if they reach the receiver.

To emphasize this conclusion about the nature of the head wave propagation, the GIRT simulated rays of a L-surface wave propagation all along the irregular specimen surface without any specimen bulk propagation hypothesis are shown in *Fig. 13*. To satisfy the previous condition, two constraints points are specified to the GIRT-B algorithm and are positioned on the specimen surface respectively just before and just after the surface irregularity, so as to impose the propagation of rays along the irregular surface. In that case, the surface ray is generated by critical incidence on a planar interface as described in *Fig. 1*. The corresponding extracted wave front does not match the head wave front obtained from

FEM simulations and confirms that the bulk mechanism stated previously for the head wave propagation is likely to predominate for very corrugated surfaces.

The results in the previous comparisons between GIRT and FEM show that the head wave propagation in the bulk implied by complex interactions between the wave and the surface must be taken into account to correctly model the head wave propagation on irregular surfaces. These comparisons between the developed ray tracing model (GIRT) and FEM simulations validate the choice of the GTD approach used in GIRT to model the complex interactions between an irregular surface and the waves radiated by the probe. The GIRT based on GTD principles is able to compute valid ray paths providing wave fronts in agreement with FEM simulated results in terms of both location and shape.

4. Conclusion

The modeling of TOFD configurations used in ultrasonic NDT requires the study of the head wave propagation. While analytical theories for head waves on planar interfaces are well established, the complete simulation of head waves on irregular surfaces has to be developed. In that aim, one suitable approach is to use the Geometrical Theory of Diffraction.

A generic algorithm of ray tracing between interface points (GIRT) has thus been developed using one GTD principle: the Generalized Fermat's Principle. GIRT is a specific and generic adaptation of seismic ray tracings to NDE modeling of waves propagation and to the two points ray tracing problem solving: a fast processing of the waves propagation near very irregular surfaces between two fixed points is obtained by meshing only those surfaces and the defects rather than all the volume of the propagation media like in existing seismic ray tracings. The approach is adequate for a propagation medium constituted of homogenous or weakly inhomogeneous volumes: in the latter case, the wave propagation can be modeled by

tracing straight lines in a mean homogenous volume and adding travel time fluctuations [41].

The advantages of the GIRT are the specific treatment of diffracted and creeping rays in shadow areas, the account of both any irregular surfaces of the specimen and embedded defects (both CAD defined), the wave mode conversions at interfaces or flaws, and the calculation of all waves (bulk, surface and head waves) propagating towards a predefined observation point during a TOFD inspection for NDE including both first arrival (head wave) and latter arrival waves.

By modeling the complex wave interactions with the surfaces thanks to this ray approach, GIRT is able to correctly predict the head wave time of flight and to interpret the complex waves propagation at the vicinity of an irregular interface. For very corrugated surfaces, a bulk propagation mechanism has to be taken into account for the head wave modeling.

Valid geometrical rays paths are henceforth determined for head waves using GIRT pure kinematic analysis. Use of GTD for simulation of the head wave amplitude will be investigated thereafter by modeling surface creeping rays and corner diffractions. GIRT could then lead in the future to a complete modeling of the head wave propagation on irregular interfaces.

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Figure Captions

Figure 1: A NDT inspection using TOFD technique

Figure 2: Experimental B-scan observed in the TOFD inspection of Fig. 1

Figure 3: An irregular geometry studied by TOFD technique

Figure 4: TOFD inspection measurement on the specimen including a valley of finite

extension as described in Fig. 3. a): experimental B-scan obtained when scanning the specimen in the extension direction (perpendicular to planes of Fig. 4b) and 4c). For the first left scanning positions, the probes are on a planar part (Fig. 4b) and they are then located on both sides of the valley (Fig. 4c).

Figure 5: Propagation of a HW on an irregular surface (valley consisting in several planar slopes). a) Theoretical propagation of the head wave. b) Snapshot of the field calculated by FEM at the location of the diffraction phenomena (in the yellow area of Fig 5a).

Figure 6: Various paths (color lines) resulting from several interactions with two kinds of surfaces (black lines): a surface with a corner irregularity (a) and a surface with a cylindrical irregularity (b).

Figure 7: Functional diagram of the GIRT algorithm process

Figure 8: TOFD inspection used for the theoretical validation of GIRT.

Figure 9: Comparison of times of flight calculated both with GIRT and with FEM simulations (Civa/Athena) versus slope angles for different inspection directions (a: 45° , b: 60° , c: 75°).

Figure 10: Diffraction of L-waves on curved objects. Head wave ray paths calculated by GIRT are represented in white and forms the simulated wave front in black. FEM simulated snapshot is in color code.

Figure 11: Head wave (L wave) received by the transducer. At right: zoom on the receiver.

Figure 12: Hypothesis of a T wave received by the transducer. At right: zoom on the receiver.

Figure 13: Hypothesis of a L wave received by the transducer without propagation in the specimen bulk. At right: zoom on the receiver.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 4 (b&w)

Figure 5

Figure 6

Figure 6 (b&w)

Figure 7

Figure 7 (b&w)

Figure 8

Figure 8 (b&w)

Figure 9

Figure 9 (b&w)

Figure 10 (revised)

Figure 10 (b&w) (revised)

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Figure 11 (revised)

Figure 11 (b&w) (revised)

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Figure 12 (revised)

Figure 12 (b&w) (revised)

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Figure 13 (revised)

Figure 13 (b&w) (revised)

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- This article provides a modeling study of head waves near irregular surfaces in NDT.
- Head wave propagation near such complex surfaces implies bulk mechanisms.
- A generic algorithm of ray tracing between interface points (GIRT) is developed.
- GIRT, based on Generalized Fermat's Principle, models effects of complex surfaces.
- The head wave fronts computed by GIRT are in good agreement with FEM simulations.