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

Adrien Ferrand, Michel Darmon, Sylvain Chatillon, Marc Deschamps

HAL Id: hal-01836190
https://hal.science/hal-01836190

Submitted on 3 Jan 2019

Accepted Manuscript

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

A. Ferrand, M. Darmon, S. Chatillon, M. Deschamps

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

2   **NDE**

3   **A. Ferrand[1], M. Darmon[1], S. Chatillon[1] and M. Deschamps[2]**

4   [1]CEA, LIST, Department of Imaging & Simulation for Nondestructive Testing, F-91191 Gif-

5   sur-Yvette, France.

6   [2] Univ. Bordeaux, I2M−APy, UMR 5295, 33400 Talence, France**.**

7

8   **E-mail authors:**

9   A. Ferrand: adrien.ferrand@cea.fr

10   M. Darmon: michel.darmon@cea.fr

11   S. Chatillon: sylvain.chatillon@cea.fr

12   M. Deschamps: m.deschamps@i2m.u-bordeaux1.fr

13

14   **Corresponding author:**

15   M. Darmon

16   Phone number: (+33)169082288

17   Email: michel.darmon@cea.fr

18   Postal address: CEA, LIST, Department of Imaging & Simulation for Nondestructive Testing,

19   F-91191 Gif-sur-Yvette, France.

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

2

45

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,

3

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

95 path of head waves in specimens inspected by TOFD technique. Based on an adaptation to the

96 NDE domain of seismic ray tracing algorithms, GIRT is a new method for solving the two-

97 points ray tracing problem, which is the calculation of the true ray between two defined

98 points: the source and observation points.

99 Ray-tracing techniques are often employed for modeling wave propagation in

100 electromagnetism, optics, seismology … Traditional ray tracing algorithms are the shooting

101 method [19] and the bending method [20,21]. The shooting method, well adapted for field

102 propagation modeling, fixes the source point, takes initial ray direction and then finds the

103 location of the observation point; in the view of two-points rays tracing, an iterative procedure

104 for finding the starting direction can be used to yield the desired observation point. Ray

105 bending is a variational approach which perturbs some initial estimate of the ray path, the

106 ends being fixed, until the true ray which minimizes the travel time is found. The two

107 previous traditional methods are heavy in time computation for solving the two-points ray

108 tracing problem and not efficiently adapted to deal with diffracted waves and shadow areas in

109 which head waves around irregular surfaces propagate.

110 To improve efficiency of the shooting method on the diffracted waves calculation, seismic

111 ray tracing algorithms based on a grid based scheme were developed more recently : wave

112 front construction [22], the finite difference Eikonal equation solver [23–27] which also

113 generally needs large computation time for tracing rays and Shortest Path Method (SPM)

114 algorithms [28–35] (also called minimum travel time tree - MTTT) which are relatively

115 underdeveloped algorithms based on Huygens' and Fermat's principles. Compared with the

116 traditional ray tracing algorithms, the grid based scheme has several advantages for

117   application to NDE modeling: it is able to easily locate ray paths in shadow zones; it is

118   numerically stable and can find the first arrival in complex media.

119   The current study proposes, for modeling the propagation of an incident beam towards a

120   receiving probe in a specimen of irregular surfaces including flaws, an approach based on

121   seismic SPM algorithms adapted to ultrasonic NDE and specifically designed for the two

122   points ray tracing problem. For a 2D propagation, the initial SPM Moser's algorithm [29]

123   consists in launching rays from a source, in considering in a 2D grid the adjacent node with

124   minimal travel time as a secondary source, in repeating the previous process so as to

125   propagate first arrival waves to the 2D grid nodes. More recently, Zhang et al [35] developed

126   the interface source method (ISM): as in Moser's SPM, first arrival waves still propagate

127   using a ray shooting scheme from nodes to nodes in a 2D grid but on the other hand only

128   interface points are taken as secondary sources. The developed GIRT model uses a new SPM

129   approach specifically devoted to two points ray tracing in a propagation medium constituted

130   of homogeneous volumes (in terms of sound velocity). The GIRT takes advantages that in the

131   latter case waves propagate in straight lines between interface points: only the specimen

132   interfaces are meshed (in a simple 1D mesh for a 2D propagation), the source (on the emitter)

133   and observation (on the receiver) points are added to the mesh and the wave ray path of

134   minimum travel time passing through mesh points is found between the two fixed points. One

135   of the major advantages of this GIRT method is the fast processing of very irregular surfaces

136   as only the surfaces of the specimen are meshed and not all the specimen volume like in other

137   SPM algorithms [28–35]. In addition, GIRT directly traces in an optimized manner (a two

138   points ray tracing) the shortest path from a source reaching any required observation point

139   located anywhere (outside the 2D grids needed by previous methods to propagate all shortest

140   paths to all grid nodes).

141   Furthermore, compared to the ISM method [35], the developed GIRT algorithm has

142   notably added features to meet the specificities of ultrasonic NDT applications. Firstly,

143   whereas ISM has been shown to deal with only the first arrival or one reflection path for P

144   bulk waves, the GIRT algorithm is adapted to find not only the head wave ray path (first

145   arrival) but also all complex later arrival waves including mode or nature conversion by

146   adding constraints on the searched ray path, fixing one or more points through which the ray

147   path must pass, and by defining independent types of wave propagation along each path

148   connecting the constraint points. Secondly, the GIRT can take into account all types and

149   natures of waves propagation occurring in NDE. Indeed the propagation is available not only

150   for the SH head waves studied in [15] (also called TH) but also for P and SV waves (also

151   called L and TV). Surface waves as Rayleigh waves and head waves are taken into account as

152   well as diffractions from surfaces in any kind of waves. Finally, GIRT approach is extended

153   to flaw scattering modeling since the flaws contained in the specimen are also meshed by the

154   GIRT algorithm in order to model rays diffracted from flaws. Consequently the GIRT

155   algorithm is generic for application to NDE as it can deal with any ultrasonic wave

156   propagating near irregular surfaces or flaws of any geometry (CAD defined). Finally this tool

157   is able to calculate valid geometric ray paths after interaction with interfaces or flaws. One

158   interest of the study presented in this paper is also to evaluate the applicability of such a

159   method initially based on seismic ray tracing in NDE applications for which the characteristic

160   dimensions (propagation distance or scatterer size) to the wave length ratio can be smaller than in

161   geophysics. The current study shows that GIRT leads to a better understanding of the head

162   wave propagation and its interaction with the surfaces. In that aim, a data fusion of simulated

163   results obtained by both GIRT and a FEM-based method is carried out.

164   The paper is organized as follows. The theoretical principles of the approach, the GIRT

165   algorithm process and the GIRT capabilities are described in section 2; some ray tracings and

166 wave fronts of the head wave and some later arrival waves, simulated with GIRT in 2D

167 applications, are compared for validation with FEM results in section 3.

168

169 **2. The Generic Interface Ray Tracing (GIRT) method**

170

171   The development of a ray tracing method allows a better understanding of the head wave

172 propagation on irregular surfaces by providing valid ray paths. The interest of such a study is

173 described in parts 2.1 and 2.2. The developed ray tracing method (GIRT) is generic by the fact

174 that it supports any kind of wave propagation and interaction with an irregular surface, and

175 describes the physical phenomena involved in the head wave propagation. Its theoretical

176 principles, functionalities and operating process are detailed in part 2.3.

177

178 **2.1. Head waves in planar surfaces configurations**

179

180   For a planar surface inspected in TOFD, a head wave is generated at the interface between

181 the material and the emitter and propagates in the material along the surface, and is radiated as

182 a bulk wave in the wedge, reaching the receiver. For planar surfaces, the head wave is seen as

183 the result of a critical refraction phenomenon of the incident wave on the interface between

184 the two media. *Fig. 1* describes, in a TOFD inspection of a planar specimen containing an

185 embedded crack, the propagation of different waves including the head wave.

186   *Fig. 2* illustrates the B-scan measured in the inspection described in *Fig. 1*. Three kinds of

187 signals can be observed and are characteristics of a TOFD inspection on a planar specimen.

188 These signals correspond respectively to the head wave (1), the diffraction (2, 2') of the

189 refracted bulk wave on the edges of the crack and the reflection (4) of the refracted bulk wave

190 on the specimen bottom.

191

2.2. Head wave in irregular surfaces configurations

193

194   TOFD inspections of specimen with irregular entry surfaces can be required for specific

195   NDE applications. For example, the process of repairing a material including a surface

196   breaking crack implies to remove the matter around the defect then to replace the removed

197   matter. The TOFD technique is applied on the specimen between the two reparation stages in

198   order to ensure that the entire defect has been removed. The geometry of the specimen after

199   matter removing is presented in *Fig. 3*.

200   A good understanding of the head wave propagation on such surfaces is essential for the

201   complete modeling of TOFD inspections on realistic configurations. In particular, the head

202   wave signal is one of the main references for the detection and the location of potential

203   defects in the specimen. As explained in [15], irregularities of the specimen surface induce

204   modifications on the head wave received signal compared to that observed on planar

205   interfaces. Indeed such modifications can be noticed on experiments: the B-scan presented in

206   *Fig. 4* is extracted from a TOFD inspection measurement on the specimen described in *Fig. 3*

207   and highlights two kinds of differences which can be observed when scanning over the

208   surface irregularities. Firstly, the head wave time of flight appears to be incoherent with the

209   hypothesis of head wave propagation all along the entry surface: indeed the measured travel

210   time is less than that of a surface wave propagating all along the complex surface. Secondly,

211   the irregular surface causes an important decrease (more than 15dB) of the head wave

212   amplitude compared to a planar interface.

213   To understand the physical process responsible for the observed head wave propagation on

214   complex surfaces, an analysis of the nature of the field propagating near such surfaces has

215   been carried out: the emitter generates a refracted field in the material which interacts with the

216   surface. In particular, surface corners are responsible for diffracting the field in their

217   geometrical shadow. Thus head wave propagation cannot be considered as a critical refraction

218   anymore like in the case of planar surfaces, but the result of the diffractions of the generated

219   refracted field on the surface irregularities. *Fig 5a* describes such behavior on an example of

220   irregular surface: the head wave, after a bulk refraction of the incident wave, is diffracted two

221   times on the surface corners, in order to create a diffracted wave, which is then refracted again

222   towards the receiver. In order to visualize this behavior, some numerical simulations have

223   been carried out with the hybrid technique CIVA/ATHENA [36] using both analytical models

224   and finite elements simulations near the surface irregularities. The principle of this technique

225   is the following. A volume in the specimen is defined, embedding the surface and its

226   irregularities. The field reaching the volume entry is calculated by the analytical CIVA pencil

227   method on the volume border. Then the field is propagated in the defined volume by the finite

228   elements scheme ATHENA. The results of this simulation are presented in *Fig. 5b* and show

229   that there exists a field diffracted from the surface corner in the geometrical shadow area of

230   the irregular surface: the corresponding diffracted rays well generate the head wave (*Fig 5a).*

231

232   **2.3. GIRT objectives and principles: construction of valid ray paths**

233

234   Considering the behavior of the head wave near an irregular surface, the ray theory

235   formalism is then applied for the two points ray tracing problem. The head wave propagation

236   and more generally all the waves in the specimen are then the result of specific interactions

237   between the wave field inside or outside the specimen and the specimen surface: the ray path

238   representing this propagation is the combination of specific rays connected to each other by

239   secondary source points. These secondary source points are located on the specimen surface

240   and correspond to the locus of each interaction responsible of the wave propagation. The rays

241   are a representation of the wave propagation between each secondary source points.

242   The GIRT ray tracing formalism is thus based on the Huygens principle. Considering

243   known source point M_s and observation point M_o, there exists a secondary source points

244   collection $\{M_i\}_{i \in (1,..,N)}$ located on the specimen/flaws surfaces which represents the locus of all

245   potential interactions between the wave field and the surfaces: the size N of the secondary

246   source points increases with the complexity of the surface irregularities. The ray path

247   associated to a wave propagation between the points M_s and M_o is then a combination of

248   elementary particular rays $\left(M_j M_l\right)_{(j,l) \in (s,o,1,..,N)^2}$ whose extremities are secondary source points

249   M_i among the collection $\{M_i\}_{i \in (1,..,N)}$ of an elementary ray emitted from M_s and of an

250   elementary received on M_o.

251   In the following, it is illustrated on examples (*Fig. 6*) that this principle of secondary

252   sources can be applied to represent all physical waves in a propagation medium containing

253   interfaces and flaws. In a general manner, numerous waves including the head wave are

254   emitted from a source point M_s and received on an observation point M_o: these waves are

255   characterized by their interactions with the specimen surfaces involved in their propagation

256   and then by the secondary source points constructing the associated ray path. Moreover,

257   theses interactions may be responsible of a wave mode or wave nature conversion:

258   consequently, each elementary ray $\left(M_j M_l\right)_{(j,l) \in (s,o,1,..,N)^2}$ can represent the propagation of a

259   longitudinal (L) bulk wave, transversal bulk waves (T in an isotropic medium, qT1 and qT2 in

260   anisotropic one), lateral surface wave (L or T) or Rayleigh-like (Rayleigh, Generalized

261   Rayleigh, Stoneley) wave depending on the type of interaction located on the secondary

262   source point M_j which is the departure point of ray $\left(M_j M_l\right)_{(j,l) \in (s,o,1,..,N)^2}$.

263   Two inspection configurations involving irregular surfaces are studied as examples in *Fig.*

264   *6*. The first configuration (*Fig. 6a*) is a three propagation media one for inspection of a

265   specimen including a corner irregularity on its entry surface, an internal interface with slopes

266   and a defect. The case of an isotropic elastic specimen with an entry cylindrical surface is

267   shown in *Fig. 6b*. The upper medium is a fluid one in both cases. Each ray path in *Fig. 6a* and

268   *Fig. 6b* represents one particular wave propagating. Only some ray paths among all existing

269   are shown as examples and the secondary source collection $\{M_i\}_{i \in (1,..,N)}$ is consequently not

270   exhaustive.

271   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

272   shortest time of flight and thus corresponds to the head wave propagation: its path is

273   composed of a refraction at M_2 of the longitudinal bulk wave emitted at M_s, a corner

274   diffraction at M_4 without mode or nature conversion and a refraction towards the observation

275   point M_o. However the diffraction of the L bulk wave at the corner M_5 implies also a mode

276   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

277   2 in *Fig. 6a*) with a higher time of flight than the head wave ray path. The ray path

278    $M_s M_3 M_4 M_5 M_7 M_{10} M_o$ (path 3) is associated to a L bulk wave critically refracted at M_3 into a

279   L lateral wave which propagates along the surface and is critically reradiated at M_{10} into a

280   bulk L wave. As another example the secondary source point M_7 also converts the lateral

281   wave into a Rayleigh wave which radiates at M_9 a bulk L wave and gives the ray path

282    $M_s M_3 M_4 M_5 M_7 M_9 M_o$ (path 4). Finally the ray path $M_s M_1 M_6 M_8 M_{13} M_o$ (path 5) corresponds

283   to a L bulk wave emitted at M_s and refracted at M_1 which is reflected on the internal

284   interface of the specimen on M_6 and diffracted on the edge defect on M_8 before reaching

285   M_o.

286   *Fig. 6b* shows the ray paths of different waves which propagate close to a surface with a

287   cylindrical irregularity. The head wave propagation is associated to the shortest ray path

288    $M_s M_1 M_4 M_5 M_9 M_o$ (path 1): the emitted L bulk wave is refracted in the specimen at M_1 and

289   diffracted on the cylindrical irregularity in a surface creeping ray $M_4 M_5$; the wave propagates

290   along the irregularity and is then radiated again at M_5, and refracted at M_9 towards the

291   observation point M_o. Similarly to the path 3 of *Fig. 6a* along the corner irregularity, the ray

292   path 2 ($M_s M_2 M_3 M_6 M_8 M_o$) represents the L lateral wave propagation along the cylindrical

293   irregularity generated by a critical refraction at M_2 and the critical radiation at M_8. A

294   Rayleigh wave is also created at M_6 which radiates at M_7 and give the path 3

295    $M_s M_2 M_3 M_6 M_7 M_o$.

296   Ray paths not shown on *Fig. 6a* and *Fig. 6b* result from other interactions in the specimen.

297   For example, mode conversion of the emitted L bulk wave occurs at the refraction on the

298   entry surface, at specular reflections or at diffractions on the specimen surface irregularities or

299   flaws (like at M_8 in *Fig. 6a*) and allows the propagation of several transversal bulk waves

300   into the specimens. Mode conversions of bulk waves into Rayleigh-like waves also occurs on

301   surface irregularities (at M_4, M_5, … in *Fig. 6a* or M_3 in *Fig. 6b*).

302   Finally the purpose of the GIRT is to find all physical paths described above in isotropic or

303   anisotropic media using the Generalized Fermat's Principle. This principle is a basic one of an

304   asymptotic ray theory, the Geometrical Theory of Diffraction (GTD) [37] which extends

305   Geometrical Acoustics by adding rays diffracted from canonical scatterers (edges, corners,

306   curved smooth objects…) to the classical geometrical (refracted and reflected) rays. In the

307   aim of ray tracing, the Generalized Fermat's Principle allows to determine if a ray path

308   represents a physical wave propagation and is consequently valid. Indeed this principle

309   indicates that the valid ray path for a wave resulting from particular interactions between the

13

310   wave field and surfaces and is the one providing the stationary time of flight and respecting

311   the predefined conditions imposed to the wave propagation (choice of the modes for

312   instance). This principle is verified by finding the minimal time of flight and the associated

313   ray path. Consequently the principle of the GIRT is to find the valid ray path respecting the

314   Generalized Fermat's principle and achieving the wave propagation conditions using a time of

315   flight minimization technique. Its algorithm process is described in the following section.

316

317   **2.4. GIRT algorithm process**

318

319   The steps of GIRT algorithm process are described in this section for the general case of

320   anisotropic media and schematically represented in the functional diagram of *Fig. 7*. This

321   algorithm process is the subject of a patent filing [38].

322   This process is first described when used for determination of the head wave path, the first

323   arrival (like the paths 1 on *Fig. 6a* and *Fig. 6b*) and is called in that case GIRT-A. The input

324   data (step 1) of the GIRT are the CAO description of the specimen in which the ray path has

325   to be calculated, the source and observation points which are the ray extremity points, the

326   slowness surfaces for the wave propagation mode desired inside and outside the specimen, the

327   description of defects inside the specimen and the discretization fineness of the specimen or

328   flaw surfaces which defines the calculation accuracy.

329   Indeed the next steps of the algorithm process is the discretization of both each specimen

330   surface (step 2) and of each existing defect (step 3) in order to deal with any irregular surface:

331   for the configuration of *Fig. 6a,* the two irregular surfaces and the planar defect are meshed.

332   The obtained discretization points collection $\{M_i\}_{i\in(1,..,N)}$ constitutes the secondary sources

333   collection for waves diffraction as stated by the Huygens principle in a propagation medium

334   constituted of homogeneous volumes. Consequently these secondary sources are possible M_i

335   points composing the ray path as described in section 2.3. The GIRT at this step 2 uses a

336   similar approach to the interface source method (ISM) developed by Zhang and al [35] since

337   interface points are seen as secondary sources.. On the other hand, the discretization carried

338   out by GIRT differs from that performed by ISM [35] and other SPM algorithms [29]. Indeed

339   as only the surfaces and the defects are discretized, the ray path searching is done only

340   through secondary sources located along the specimen and defects surfaces and not trough a

341   grid covering all the specimen volume. The obtained secondary sources collection has a

342   limited size N compared to that generated from a volume discretization and provide a more

343   stable and faster research of ray paths.

344   To determine the valid secondary sources involved in the searched ray path in the view of

345   the two points ray tracing problem, the elementary paths between two secondary sources are

346   calculated (step 4): an elementary path represents the wave propagation along a direct path

347   involving two and only two M_i secondary sources without any other diffraction effect. All

348   the valid elementary paths between two M_i points respecting the previous condition are

349   calculated for all the M_i points and the associated elementary times of flight are deducted

350   from the slowness surfaces given and stored by the algorithm process (step 5). As an example,

351   the ray M_2M_5 in *Fig. 6b* is an elementary ray path of the path 1 and path 2.

352   A secondary sources collection, an elementary paths collection and an associated

353   elementary times of flight collection have been obtained during the previous steps. The M_s

354   source and M_o observation points are added in step 6 to the existing secondary sources

355   collection and all the new valid elementary paths involving one of these two points are

356   calculated and taken into account in the collections. The interest of having separated this step

357   6 from step 5 is to allow the ray path calculation for different couples of source and

358   observation points but with the same specimen without needing to recalculate at each ray

15

359   calculation all the other elementary paths in the specimen (already independently determined

360   at step 5).

361   Finally, knowing the secondary sources collection and the elementary paths collection, the

362   search for the valid wave ray path in the view of the two point ray tracing reduces to an

363   optimization problem. It indeed corresponds to the determination of which secondary sources

364   M_i are involved in the ray path and then which elementary rays $\left(M_j M_l\right)_{(j,l)\in(1,...,N)^2}$ compose

365   the ray path associated to the minimal time of flight. This approach is called the Shortest Path

366   Method (SPM) [29] in the seismic domain and is applied in the GIRT (step 7). The secondary

367   source points collection are the nodes of an oriented graph. In this graph, two different

368   vertices are connected by an elementary ray path included in the collection. At each path is

369   associated a cost which is the elementary time of flight between of the path. Once the graph is

370   obtained, the optimal route (leading to the shortest time of flight between the source and

371   observation points) is obtained by the classical Dijkstra algorithm [39], which has the major

372   advantage to be a fast route search algorithm since all possible routes are not calculated: only

373   the most likely optimal routes are taken into account. At that step, the GIRT algorithm differs

374   strongly from the ISM developed by Zhang and al [35]. ISM is conceived to perform ray

375   shooting in a grid meshing all the volume by launching rays from a source in all directions

376   and by propagating first arrival waves from nodes to nodes in the grid: consequently a ray

377   path reaching a predefined observation point cannot be found directly notably if this point is

378   not a grid node. In GIRT, the application of the Dijkstra algorithm on the secondary sources

379   collection is well fitted and specific of the two point ray tracing problem. Indeed, the source

380   and observation points have been integrated in the secondary sources collection so that the

381   fast route search gives directly the valid ray path between these two points.

382   Later arrival waves (for example all paths represented in *Fig. 6a* and *Fig. 6b* except the

383   paths 1) can also be modeled by a GIRT-B version by adding constraints on the searched ray

16

384 path, fixing one or more points through which the ray path must pass. In the case of a ray path

385 calculation with obligatory points of passage, the GIRT-B process differs from that previously

386 described for the head wave ray path (GIRT-A process) only by some slight changes. First,

387 the GIRT-B inputs include in addition the list of sorted constraint points and the definition of

388 independent types of wave propagation along each path connecting these points. Then the

389 GIRT-B operates as follows: a couple of points is formed by the source point and the first

390 constraint point, then several other couples by two adjacent constraint points and the last

391 couple by the last constraint point and the observation point. An optimized ray is then

392 searched between the two points of each couple: in that aim, the previous points are seen as

393 the source and observation points for GIRT-A process and the GIRT-A process is

394 consequently carried out independently for each couple, the latter having its own type of

395 propagation, allowing all type of wave propagation in the specimen. At last, all the calculated

396 couples ray paths are concatenated to obtain the complete ray path between the source and

397 observation points.

398

399 **2.5. GIRT capabilities**

400

401 GIRT is thus a generic algorithm calculating geometrical paths and the corresponding ray

402 time of flight propagating in isotropic or anisotropic media. It has been designed to determine

403 the valid ray path between two points assuming one or several given interactions between the

404 current ray and the irregular surface. The two points can be located anywhere inside or

405 outside the specimen.

406 Two kinds of interactions, accounted by GTD [37], are supported by GIRT: diffraction on

407 smooth objects, leading to surface creeping rays (see the ray $M_5 M_6$ on *Fig. 6b)*, and

408 diffraction on wedges or edges (see *Fig. 6a)*, leading to bulk or surface diffracted rays.

409 Furthermore, the propagation of numerous wave modes is taken into account with potential

410 mode conversion at the surface: the longitudinal and transversal modes (possibly occurring

411 for different kinds of waves: bulk waves, lateral waves, reradiated head waves or surface

412 waves…), and the surface Rayleigh-like waves.

413   All the ray paths presented on *Fig. 6a* and *Fig. 6b* are modeled by setting some wave

414 propagation conditions supported by the GIRT. As an example the head wave ray paths 1 of

415 *Fig. 6a* and *Fig. 6b* are calculated using by finding the shortest ray path for a longitudinal

416 bulk wave without mode conversion. The ray path 2 of *Fig. 6a* is found for the condition of a

417 wave propagation with the shortest time of flight and a mode conversion from L bulk to T

418 bulk on the surface irregularity. The ray path 3 of *Fig. 6a* and the ray path 2 of *Fig. 6b* are

419 modeled imposing a surface propagation condition (detailed in the comments of *Fig. 14*) to

420 the ray path in order to propagate lateral waves along the specimen surface. Similarly the ray

421 path 4 of *Fig. 6a* and ray path 3 of *Fig. 6b* are found using the same surface propagation

422 condition and that of a wave mode conversion from a lateral wave to a Rayleigh wave. Finally

423 the ray path 5 of *Fig. 6a* is calculated using a reflection condition on the internal surface and

424 an obligatory point of passage M_8 on the defect edge.

425   Thanks to the previously described capabilities, all the interactions occurring in the case of

426 an irregular surface and presented in this section are modeled by GIRT. In next Part 3 of this

427 paper, GIRT is applied to the head wave path modeling in TOFD near irregular surfaces and

428 only the waves which may be responsible of the head wave propagation or examples of the

429 least later arrival waves are studied. It is shown in Part 3 that GIRT provides accurate

430 predictions for the time of flight and wave fronts of both the head wave and even later

431 propagation waves in TOFD near irregular surfaces.

432

18

433 **3. GIRT simulated results and theoretical validations**

434

435 Calculations using GIRT of ray paths and wave fronts are shown in this section in the aim of

436 modeling the propagation of head waves near irregular surfaces in some TOFD

437 configurations. Such simulations are compared and superimposed to FEM ones.

438

439 **3.1. Validation of the head wave time of flight**

440

441   A theoretical validation of GIRT is performed by comparing times of flight calculated with

442 both GIRT and finite-elements (FEM) simulations obtained with CIVA/Athena, which is

443 considered here as a reference model. The comparison deals with TOFD inspection

444 simulations for several inspection directions ($\theta = 45°$, $60°$ and $75°$ where θ is the angle

445 defined in *Fig. 8*) with L waves emitted at 5MHz. The specimen is a planar stainless steel

446 block which is inspected using two contact planar rectangular transducers (6mm*5mm). The

447 specimen entry surface has two slopes. The head wave path determined by GIRT is illustrated

448 in blue in *Fig. 8* and includes a diffraction on the surface corner.

449   The times of flight obtained by GIRT have been compared to the results of the FEM

450 simulation software for different slope angles and are shown in *Fig. 9*. Each graph of the *Fig.*

451 *9* is associated to a particular inspection direction (from L45° to L75°), the solid lines are the

452 results obtained with the GIRT and the dashed lines are the results obtained by FEM

453 simulations.

454   The graphs show a very good concordance between the results of the GIRT and FEM

455 simulation, for each direction of inspection and any slope angle. The GIRT is then able to

456 calculate the head wave time of flight with a very good precision (error less than 0.1%). The

457 simulated times of flight of the head wave signal received by the probe are almost

19

458 independent of the inspection directions because the head wave signal is generated by only

459 some refracted rays included in the beam radiated in the specimen by the emitter surface,

460 those rays being close to the mean head wave path shown in blue in *Fig. 8* including a

461 diffraction on the corner.

462

463 **3.2. Analysis of the propagation of waves in the surface shadow**

464

465 Additional finite-element simulations on CIVA/Athena have been performed on irregular

466 surfaces including curved parts, and the propagation wave field in the material at different

467 times is also visualized on FEM snapshots. In this section, GIRT has been employed in the

468 aim of identifying the nature of waves propagation corresponding to some observed

469 wavefronts in the FEM snapshots.

470 Indeed, when studying the interaction on a beam with an irregular surface, numerous wave

471 fronts are generated. For instance *Fig. 10* shows FEM simulation of the waves propagation

472 near a curved valley constituted of two curved edges separated by a planar part. Numerous

473 wave fronts are observed in the FEM snapshot of *Fig. 10*, which highlights the great number

474 of interactions occurring between the refracted field and the specimen. The nature of some of

475 these wave fronts (numerated in *Fig. 10*) can be easily guessed. The surrounded front L1

476 corresponds to the direct L-wave refracted in the specimen by the emitter. The front L1 is

477 reflected by the specimen bottom (dashed black horizontal line in *Fig. 10*) creating the L-

478 wave front L2 and T-wave front T1. T2 refers to T-waves refracted in the specimen. Other

479 wave fronts are of more complex nature. It is consequently of interest to identify the nature of

480 rays which have generated the observed wave fronts in the FEM simulations.

481 So as to identify the nature of one particular FEM wave front, the following methodology

482 is chosen:

20

483   -   The studied wave front is identified on the FEM snapshot as the local maximum of the

484   displacement field.

485   -   An appropriate hypothesis on the wave propagation and interactions with the surface is

486   formulated by the GIRT user to explain the generation of the studied wave front.

487   Considering the previously chosen path hypothesis, GIRT builds rays until their time of

488   flight reach the FEM snapshot time.

489   -   The resulting wave front simulated by GIRT is then drawn for the FEM snapshot time

490   by tracing the curve orthogonal to every ray found at this time of flight [40]. The GIRT

491   simulated wave front is superimposed to the FEM snapshot and its location compared

492   to that of the FEM studied wave front to validate the chosen propagation hypothesis.

493   In the present study, identification of wave fronts nature by comparing FEM and GIRT

494   simulations is done only for wave fronts relevant for studying head waves propagation. But a

495   similar analysis could be performed for all the other wave fronts observed on FEM snapshots.

496   The method is thus applied for the following wave fronts:

497   -   The front of the refracted L-wave (*Fig. 10*), whose diffraction on the second curved

498   part of the surface specimen is responsible of head wave propagation towards the

499   receiver (as said in section 2.2).

500   -   The L head wave (*Fig. 11 and 13*), received at first on the receiver.

501   -   The T wave received just after the L head wave on the receiver.

502   For each figure, the ray paths (white lines) and the front (dashed black line) simulated by

503   GIRT are superimposed to the studied FEM snapshot (in color code).

504   In *Fig. 10*, ray paths simulated by GIRT are obtained considering the hypothesis injected in

505   GIRT of a diffraction of the refracted L-wave field on a curved object without mode

506   conversion and without constraint point. Ray paths are thus built with the GIRT-A algorithm

507   between one source point (emitter center) and a set of observation points located in the

508   specimen bulk after the second curved part at right, inside the shadow areas formed by the

509   surface irregularity. The GIRT objective is here to determine between the source and each

510   observation point the shortest path which corresponds to the head wave path. The calculated

511   ray path indicates that the emitted wave is refracted in the specimen bulk, before being

512   diffracted by the first curved object at left. The GIRT modeling of the diffracted field by near

513   this curved part reveals creeping rays. Indeed, the refracted longitudinal rays reaching

514   tangentially the first curved object are converted into creeping rays. These creeping rays are

515   then diffracted into both bulk rays along their curved propagation and a surface ray which

516   propagates along the planar surface. The surface ray is converted again at the junction with

517   the second curved part into a creeping ray which is diffracted into bulk rays generated

518   tangentially to the second curved object at right inside the shadow area caused by the surface

519   irregularity. As seen in *Fig. 10*, the calculated wave front is the result of the wave diffractions

520   on the two curved objects. The previously described head wave propagation is validated by

521   comparing the GIRT and FEM simulated wave fronts and observing a good agreement

522   between them.

523   The following two cases, presented in *Fig 11* and *Fig 12* are obtained with the same

524   configuration as in *Fig. 10*, but the propagation of waves is extended up to the receiver,

525   allowing observing the wave fronts received in experimental studies. As in *Fig. 10*, the

526   refracted longitudinal wave is diffracted by the curved parts at left and at right and refracted

527   again at the last surface between the specimen and the wedge of the receiving probe. Two

528   different hypotheses detailed hereafter are inputted in GIRT concerning the second refraction

529   (at the interface specimen/wedge of the receiver) and give the results of respective *Fig. 11* and

530   in *Fig. 12*. In *Fig. 11*, a second refraction of longitudinal waves without mode conversion is

531   assumed and GIRT-A is used to calculate the shortest rays between the source an observation

532   points located on the receiver crystal surface. In *Fig. 12*, a second refraction with conversion

22

533   of the L wave into a T wave is supposed. To apply the last hypothesis, a constraint point is

534   defined on the plane part of the irregularity and the GIRT-B algorithm is used so as to

535   calculate the rays using the following assumptions: when the path takes place inside the

536   specimen, it is always travelled at the celerity of the L wave; when the path takes place both

537   outside the specimen and from the source point to the constraint point (i.e. in the emitter

538   wedge), it is travelled at the celerity of the L wave; when the path takes place both outside the

539   specimen and from the constraint point to the receiver point (i.e. in the receiver wedge), it is

540   travelled at the celerity of the T wave. By this way ray paths calculated by the GIRT-B satisfy

541   the mode conversion L-T condition on the surface near the receiver. As in *Fig. 10* and for the

542   two cases in *Fig. 11* and *Fig. 12*, wave fronts calculated by GIRT perfectly match with two

543   different wave fronts simulated by FEM. Furthermore the wave of type T (*Fig. 12*) is received

544   by the receiver later than that of type L (*Fig. 11)* as shown by comparing the location of their

545   corresponding wave fronts for a fixed time of flight. Consequently, in the previous

546   configuration, the head wave observed at the receiver which is by definition the first received

547   wave logically mainly corresponds to a complete path without mode conversion involving

548   only faster L waves. All the other FEM simulated wave fronts obtained in the snapshot of *Fig.*

549   *11* lead to later arrival times if they reach the receiver.

550   To emphasize this conclusion about the nature of the head wave propagation, the GIRT

551   simulated rays of a L-surface wave propagation all along the irregular specimen surface

552   without any specimen bulk propagation hypothesis are shown in *Fig. 13*. To satisfy the

553   previous condition, two constraints points are specified to the GIRT-B algorithm and are

554   positioned on the specimen surface respectively just before and just after the surface

555   irregularity, so as to impose the propagation of rays along the irregular surface. In that case,

556   the surface ray is generated by critical incidence on a planar interface as described in *Fig. 1*.

557   The corresponding extracted wave front does not match the head wave front obtained from

558   FEM simulations and confirms that the bulk mechanism stated previously for the head wave

559   propagation is likely to predominate for very corrugated surfaces.

560   The results in the previous comparisons between GIRT and FEM show that the head wave

561   propagation in the bulk implied by complex interactions between the wave and the surface

562   must be taken into account to correctly model the head wave propagation on irregular

563   surfaces. These comparisons between the developed ray tracing model (GIRT) and FEM

564   simulations validate the choice of the GTD approach used in GIRT to model the complex

565   interactions between an irregular surface and the waves radiated by the probe. The GIRT

566   based on GTD principles is able to compute valid ray paths providing wave fronts in

567   agreement with FEM simulated results in terms of both location and shape.

568

569   **4. Conclusion**

570

571   The modeling of TOFD configurations used in ultrasonic NDT requires the study of the

572   head wave propagation. While analytical theories for head waves on planar interfaces are well

573   established, the complete simulation of head waves on irregular surfaces has to be developed.

574   In that aim, one suitable approach is to use the Geometrical Theory of Diffraction.

575   A generic algorithm of ray tracing between interface points (GIRT) has thus been

576   developed using one GTD principle: the Generalized Fermat's Principle. GIRT is a specific

577   and generic adaptation of seismic ray tracings to NDE modeling of waves propagation and to

578   the two points ray tracing problem solving: a fast processing of the waves propagation near

579   very irregular surfaces between two fixed points is obtained by meshing only those surfaces

580   and the defects rather than all the volume of the propagation media like in existing seismic ray

581   tracings. The approach is adequate for a propagation medium constituted of homogenous or

582   weakly inhomogeneous volumes: in the latter case, the wave propagation can be modeled by

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

584   The advantages of the GIRT are the specific treatment of diffracted and creeping rays in

585   shadow areas, the account of both any irregular surfaces of the specimen and embedded

586   defects (both CAD defined), the wave mode conversions at interfaces or flaws, and the

587   calculation of all waves (bulk, surface and head waves) propagating towards a predefined

588   observation point during a TOFD inspection for NDE including both first arrival (head wave)

589   and latter arrival waves.

590   By modeling the complex wave interactions with the surfaces thanks to this ray approach,

591   GIRT is able to correctly predict the head wave time of flight and to interpret the complex

592   waves propagation at the vicinity of an irregular interface. For very corrugated surfaces, a

593   bulk propagation mechanism has to be taken into account for the head wave modeling.

594   Valid geometrical rays paths are henceforth determined for head waves using GIRT pure

595   kinematic analysis. Use of GTD for simulation of the head wave amplitude will be

596   investigated thereafter by modeling surface creeping rays and corner diffractions. GIRT could

597   then lead in the future to a complete modeling of the head wave propagation on irregular

598   interfaces.

599

600   **References**

601

602   [1]   L.M. Brekhovskikh, Waves in layered media, Academic press New York, 1960.
603   [2]   K. Friedrichs, J.B. Keller, Geometrical acoustics. II. Diffraction, reflection, and
604   refraction of a weak spherical or cylindrical shock at a plane interface, J. Appl. Phys. 26
605   (1955) 961–966.
606   [3]   V. Červený, R. Ravindra, Theory of seismic head waves, University of Toronto Press
607   (Toronto), 1971.
608   [4]   L. Cagniard, E.A. Flinn, C.H. Dix, W.G. Mayer, Reflection and Refraction of
609   Progressive Seismic Waves, Phys. Today. 16 (1963) 64.
610   [5]   A. De Hoop, A modification of Cagniard's method for solving seismic pulse problems,
611   Appl. Sci. Res. Sect. B. 8 (1960) 349–356.
612   [6]   H. Uberall, Surface waves in acoustics, in Physical Acoustics 10 (W. P. Mason
613   and R. N. Thurston, eds.), Academic Press, New York (1973) pp. 1-60.

614 [7] J. Goodier, R. Bishop, A note on critical reflections of elastic waves at free surfaces, J.
615   Appl. Phys. 23 (1952) 124–126.
616 [8] S. Mahaut, M. Darmon, P. Benoist, P. Calmon, TOFD inspection simulation using Civa
617   software, in: Proc. BINDT, 2007.
618 [9] S. Chaffaï, M. Darmon, S. Mahaut, R. Menand, Simulation Tools for TOFD Inspection
619   in CIVA Software, in: Proc. 6th ICNDE, 2007.
620 [10] Assessment, Management of ageing of major nuclear power plant components
621   important to safety primary piping in PWRs, Vienna: IAEA, 2003.
622 [11] M. Darmon, S. Chatillon, S. Mahaut, L. Fradkin, A. Gautesen, Simulation of disoriented
623   flaws in a TOFD technique configuration using GTD approach, in: AIP Conf. Proc.,
624   2008: p. 155.
625 [12] V. Zernov, L. Fradkin, M. Darmon, A refinement of the Kirchhoff approximation to the
626   scattered elastic fields, Ultrasonics. 52 (2012) 830–835.
627 [13] G. Huet, M. Darmon, A. Lhémery, S. Mahaut, Modelling of corner echo ultrasonic
628   inspection with bulk and creeping waves, in: Ultrason. Wave Propag. Non Homog.
629   Media, Springer, 2009: pp. 217–226.
630 [14] S. Mahaut, G. Huet, M. Darmon, Modeling of corner echo in UT inspection combining
631   bulk and head waves effect, in: AIP Conf. Proc., 2009: p. 73.
632 [15] H. Zhou, X. Chen, Ray path of head waves with irregular interfaces, Appl. Geophys. 7
633   (2010) 66–73.
634 [16] I. Lerche, N. Hill, A mean-field solution of the reflection of a spherical acoustic wave
635   from a rough interface, J. Math. Phys. 26 (1985) 1420.
636 [17] I. Lerche, On the reflection of acoustic waves from a slightly curved interface, J.
637   Acoust. Soc. Am. 81 (1987) 611.
638 [18] D.P. Hill, Critically refracted waves in a spherically symmetric radially heterogeneous
639   earth model, Geophys. J. Int. 34 (1973) 149–177.
640 [19] B. Julian, D. Gubbins, Three-dimensional seismic ray tracing, J Geophys. 43 (1977) 95–
641   114.
642 [20] Y. Wang, G.A. Houseman, Tomographic inversion of reflection seismic amplitude data
643   for velocity variation, Geophys. J. Int. 123 (1995) 355–372.
644 [21] Y. Wang, Seismic amplitude inversion in reflection tomography, Pergamon, 2003.
645 [22] V. Vinje, E. Iversen, H. Gjøystdal, Traveltime and amplitude estimation using
646   wavefront construction, Geophysics. 58 (1993) 1157–1166.
647 [23] J. Vidale, Finite-difference calculation of travel times, Bull. Seismol. Soc. Am. 78
648   (1988) 2062–2076.
649 [24] J.E. Vidale, Finite-difference calculation of traveltimes in three dimensions,
650   Geophysics. 55 (1990) 521–526.
651 [25] K. Koketsu, others, Finite difference traveltime calculation for head waves travelling
652   along an irregular interface, Geophys. J. Int. 143 (2000) 729–734.
653 [26] N. Rawlinson, M. Sambridge, Multiple reflection and transmission phases in complex
654   layered media using a multistage fast marching method, Geophysics. 69 (2004) 1338–
655   1350.
656 [27] M. De Kool, N. Rawlinson, M. Sambridge, A practical grid-based method for tracking
657   multiple refraction and reflection phases in three-dimensional heterogeneous media,
658   Geophys. J. Int. 167 (2006) 253–270.
659 [28] I. Nakanishi, K. Yamaguchi, A numerical experiment on nonlinear image reconstruction
660   from first-arrival times for two-dimensional island arc structure, J. Phys. Earth. 34
661   (1986) 195–201.
662 [29] T. Moser, Shortest path calculation of seismic rays, Geophysics. 56 (1991) 59–67.

663 [30] S. Cao, S. Greenhalgh, Calculation of the seismic first-break time field and its ray path
664   distribution using a minimum traveltime tree algorithm, Geophys. J. Int. 114 (1993)
665   593–600.
666 [31] H.J. Van Avendonk, A.J. Harding, J.A. Orcutt, W.S. Holbrook, Hybrid shortest path and
667   ray bending method for traveltime and raypath calculations, Geophysics. 66 (2001) 648–
668   653.
669 [32] A. Zhao, Z. Zhang, J. Teng, Minimum travel time tree algorithm for seismic ray tracing:
670   improvement in efficiency, J. Geophys. Eng. 1 (2004) 245.
671 [33] C. Bai, S. Greenhalgh, B. Zhou, 3D ray tracing using a modified shortest-path method,
672   Geophysics. 72 (2007) T27–T36.
673 [34] C. Bai, G. Huang, R. Zhao, 2-D/3-D irregular shortest-path ray tracing for multiple
674   arrivals and its applications, Geophys. J. Int. 183 (2010) 1596–1612.
675 [35] M.-G. Zhang, Y.-G. Jia, M.-Y. Wang, X.-F. Li, A global minimum traveltime ray
676   tracing algorithm of wavefront expanding with interface points as secondary sources,
677   Chin. J. Geophys. 49 (2006) 1046–1053.
678 [36] N. Gengembre, A. Lhémery, R. Omote, T. Fouquet, A. Schumm, A semi-analytic-FEM
679   hybrid model for simulating UT configurations involving complicated interactions of
680   waves with defects, in: AIP Conf. Proc., 2004: p. 74.
681 [37] J.B. Keller, Geometrical theory of diffraction, JOSA. 52 (1962) 116–130.
682 [38] Patent filing related to GIRT in progress. Its precise reference will be given in the
683   proofs.
684 [39] E.W. Dijkstra, A note on two problems in connexion with graphs, Numer. Math. 1
685   (1959) 269–271.
686 [40] D. Bouche, F. Molinet, R. Mittra, Asymptotic methods in electromagnetics, Springer,
687   1997.
688 [41] B. Lu, M. Darmon, C. Potel, Stochastic simulation of the high-frequency wave
689   propagation in a random medium, J. Appl. Phys. 112 (2012) 054902–054902.

690

691 **Figure Captions**

692

693 Figure 1: A NDT inspection using TOFD technique

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

695 Figure 3: An irregular geometry studied by TOFD technique

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

697   extension as described in Fig. 3. a): experimental B-scan obtained when scanning the

698   specimen in the extension direction (perpendicular to planes of Fig. 4b) and 4c). For the

699   first left scanning positions, the probes are on a planar part (Fig. 4b) and they are then

700   located on both sides of the valley (Fig. 4c).

701 Figure 5: Propagation of a HW on an irregular surface (valley consisting in several planar

702   slopes). a) Theoretical propagation of the head wave. b) Snapshot of the field calculated

703   by FEM at the location of the diffraction phenomena (in the yellow area of Fig 5a).

704 Figure 6: Various paths (color lines) resulting from several interactions with two kinds of

705   surfaces (black lines): a surface with a corner irregularity (a) and a surface with a

706   cylindrical irregularity (b).

707 Figure 7: Functional diagram of the GIRT algorithm process

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

709 Figure 9: Comparison of times of flight calculated both with GIRT and with FEM simulations

710   (Civa/Athena) versus slope angles for different inspection directions (a: 45°, b: 60°, c:

711   75°).

712 Figure 10: Diffraction of L-waves on curved objects. Head wave ray paths calculated by

713   GIRT are represented in white and forms the simulated wave front in black. FEM

714   simulated snapshot is in color code.

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

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

717 Figure 13: Hypothesis of a L wave received by the transducer without propagation in the

718   specimen bulk. At right: zoom on the receiver.

719

Figure 1

Figure 1 (b&w)

Scanning

Emitter

1 : Head wave

Material

Crack

2 & 2' : Crack diffractions

3 : Reflected wave

Figure 2

Scan

Time

1 : Head wave

2 : Crack diffraction

2' : Crack diffraction

3 : Reflected wave

Figure 2 (b&w)

Figure 3

Figure 3 (b&w)

Removed part of the defect

Removed matter

Remaining matter

Remaining part of the defect

Figure 4

Figure 4 (b&w)

Figure 5

Emitter

Receiver

Incident ray in the wedge

Refraction

Refracted ray

Ray refracted in the wedge

Refraction

Diffracted ray

a)

b)

Diffracted ray

Geometrical shadow

Figure 5 (b&w)

a)

Emitter

Receiver

Incident ray in
the wedge

Ray refracted
in the wedge

Refraction

Refraction

Refracted ray

Diffracted ray

b)

Diffracted ray

*Geometrical
shadow*

Figure 6

Figure 6 (b&w)

a)

M_s M_o

surface M_1 M_2 M_3 M_4 M_7 M_9 M_{10} M_{11} M_{12} M_{13}

specimen

path 1
path 2
path 3
path 4
path 5

M_5 M_8

defect

internal interface M_6

b)

M_s M_o

surface M_1 M_2 M_3 M_6 M_7 M_8 M_9

specimen

path 1
path 2
path 3

M_4 M_5

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)

Figure 11 (revised)

Figure 12 (revised)

Figure 13 (revised)

Bottom specimen

Surface specimen

Bottom specimen
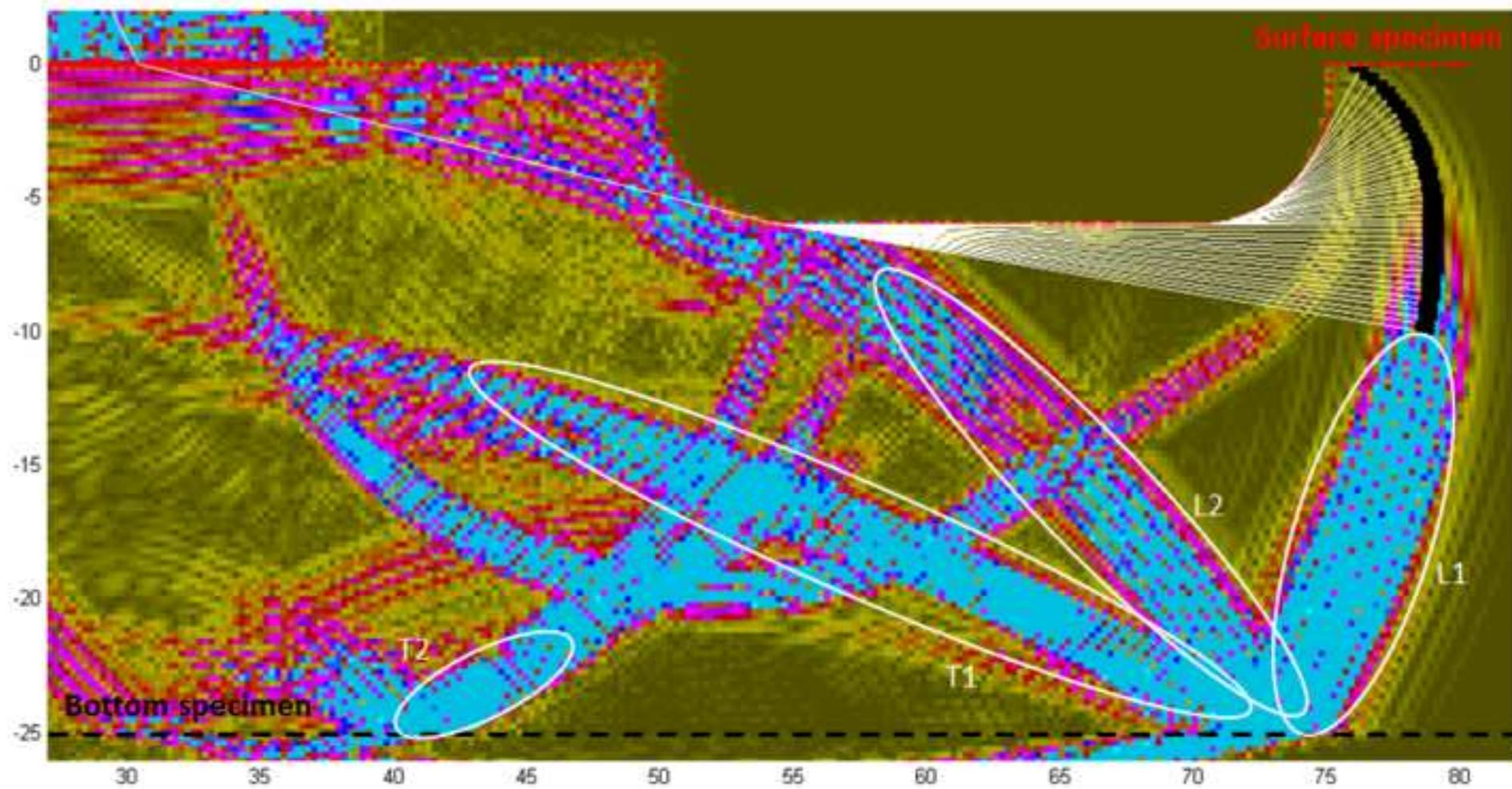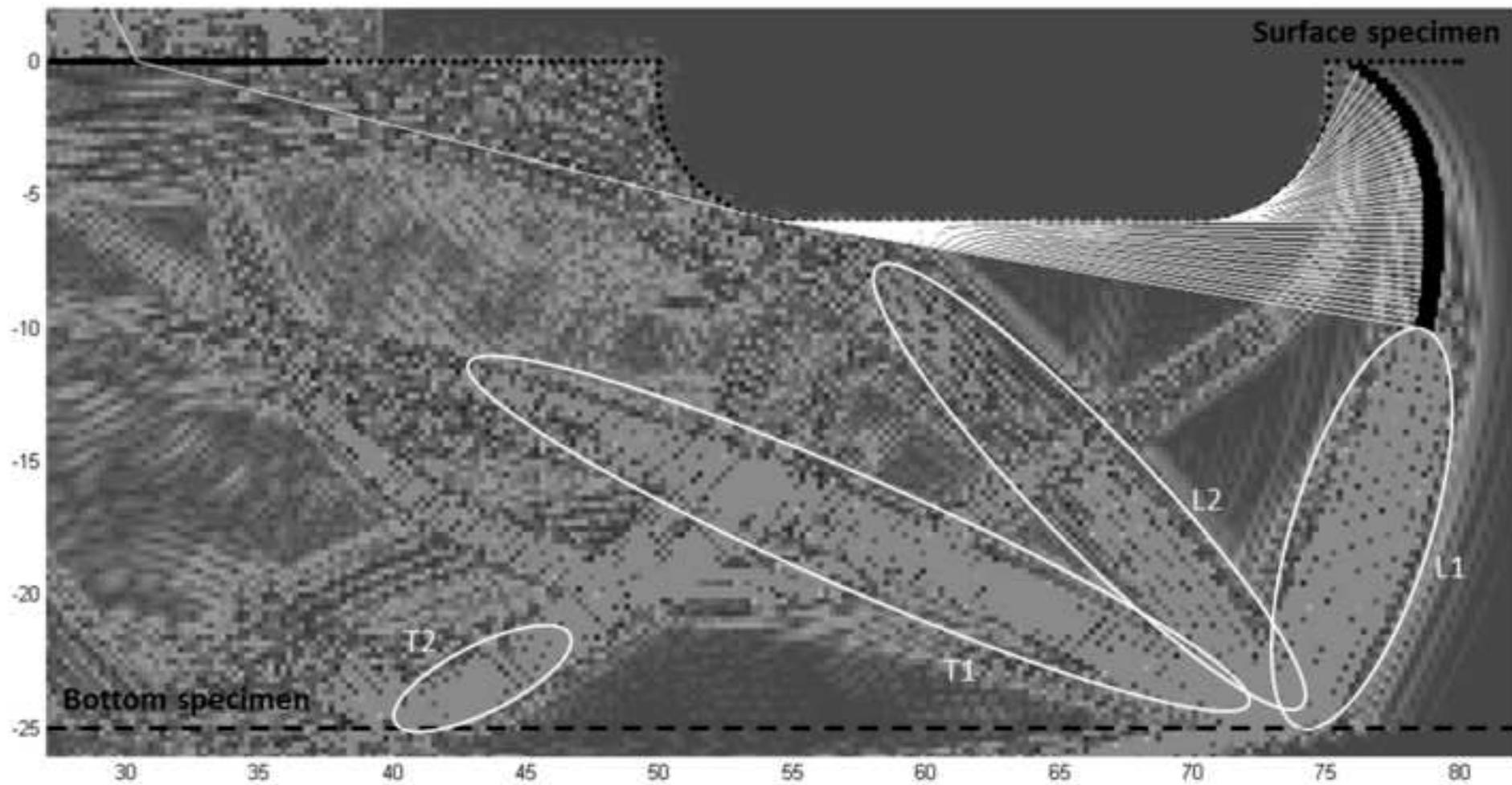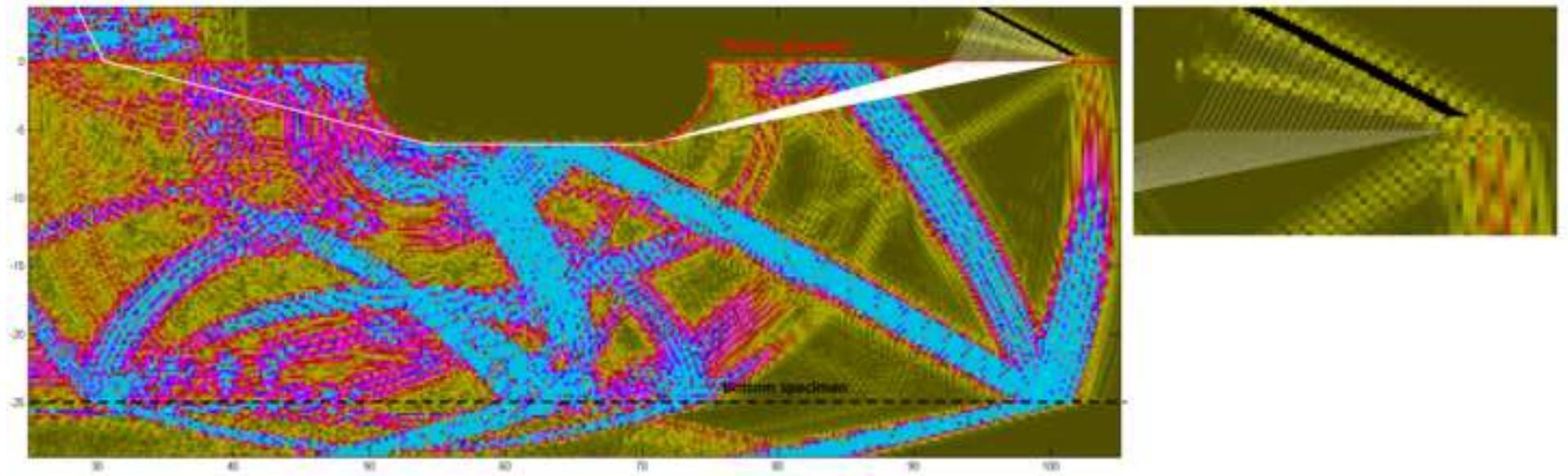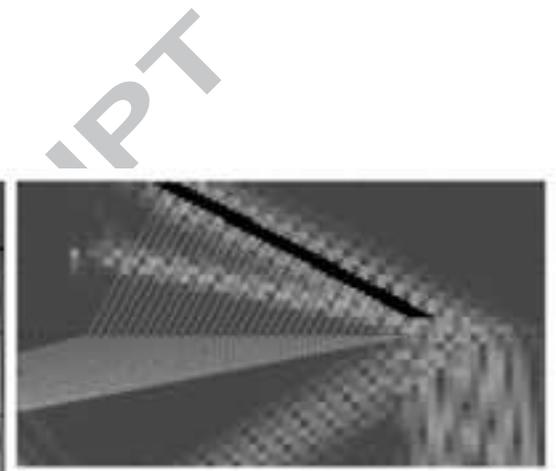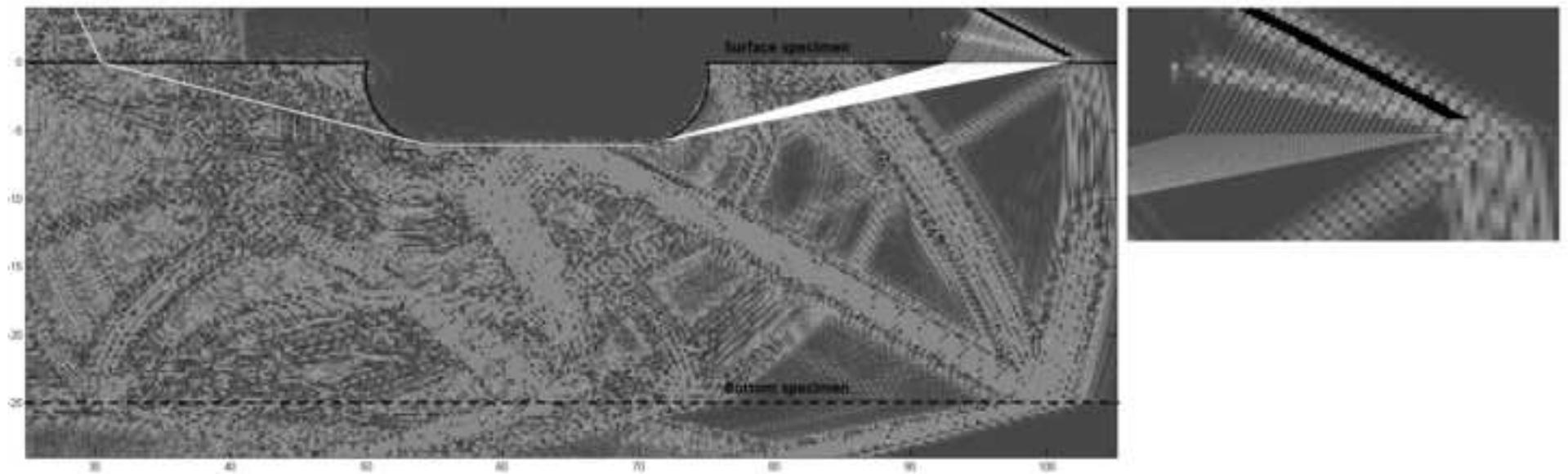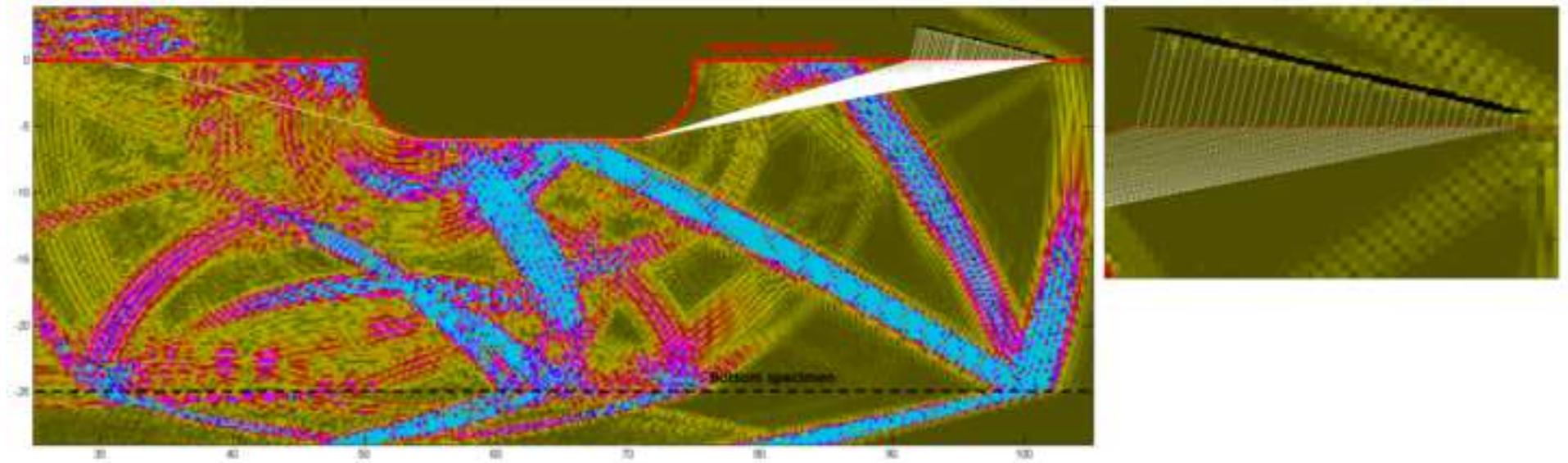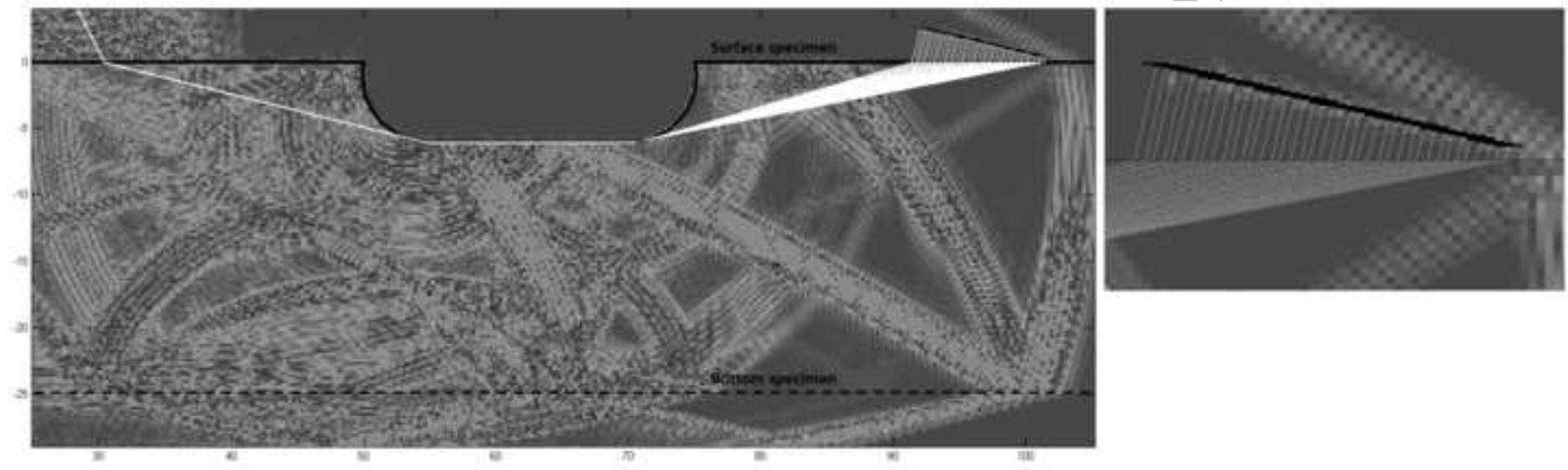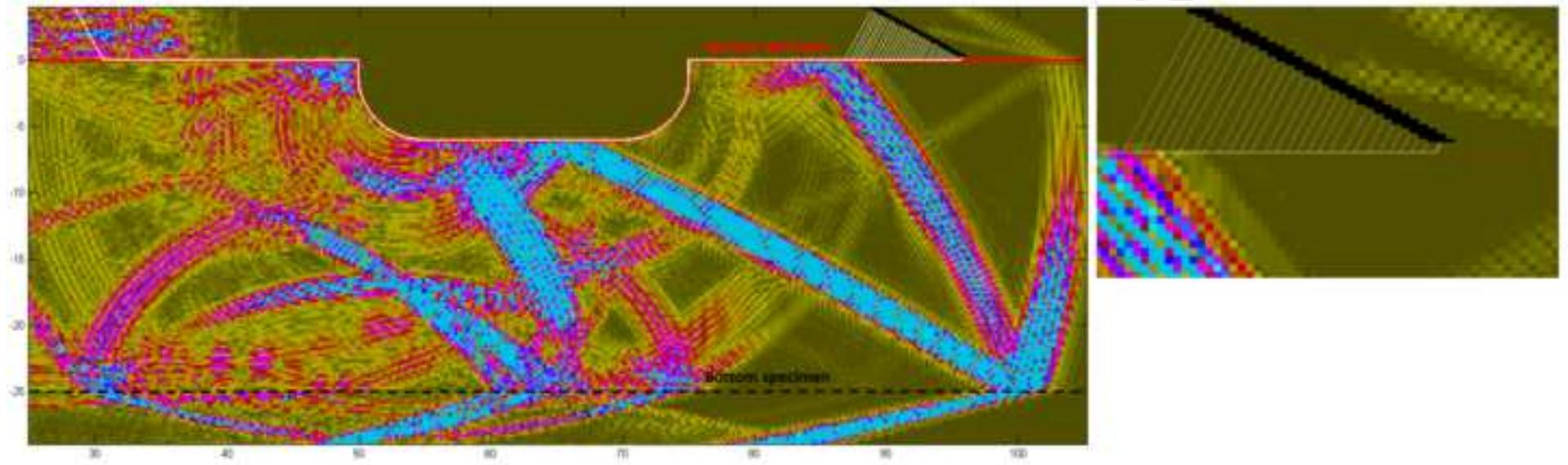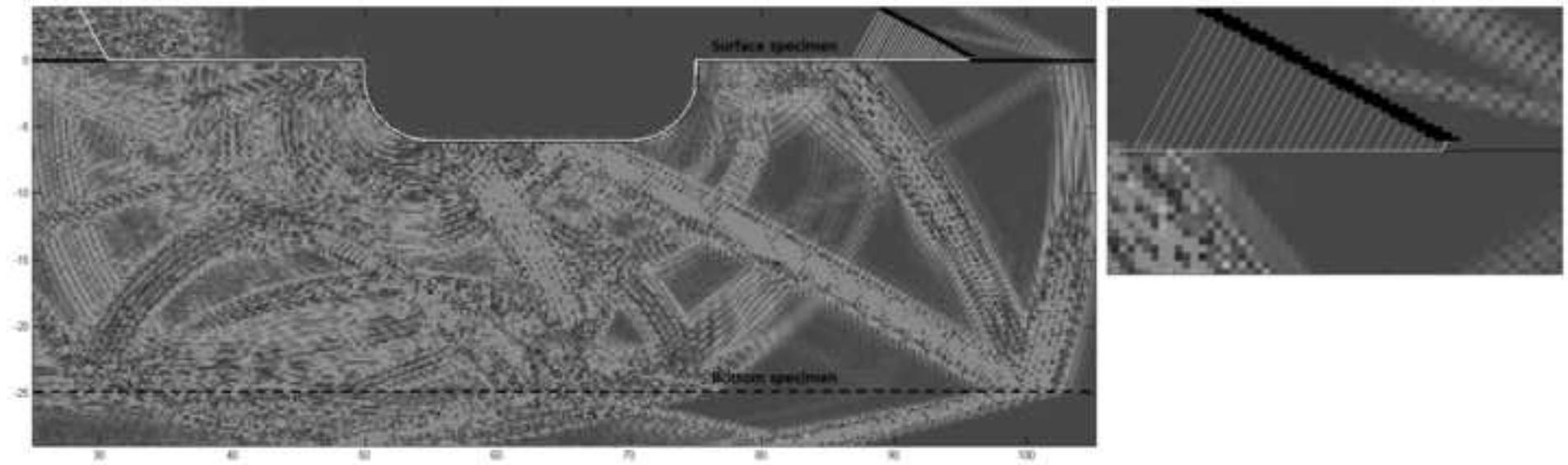
• This article provides a modeling study of head waves near irregular surfaces in NDT.

• 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.