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Recent progress in EMC and reliability for automotive applications

***Abstract**. Cable diagnosis is a crucial research topic for the reliability of embedded systems in automotive applications. This paper presents a methodology dedicated to the reflectometry analysis of branched networks in order to localize and characterize the faults which may affect it. The direct model (propagation along the cables) is modelled by a RLCG circuit model and the Finite Difference Time Domain (FDTD) method. This model provides a simple and accurate method to simulate Time Domain Reflectometry (TDR) response. Genetic algorithms are combined with this wire propagation model to solve the inverse problem and to deduce physical information's about defects from the reflectometry response.*

I. Introduction

In thirty years, the length of cables on board of cars has increased more than tenfold, from about 200 to 4000 meters [1]. As wires in automobile, trains, military and commercial aircraft, and other transportation mean are aging, they are exposed to several problems. These problems can be traced to manufacture, electrical, chemical and mechanical stresses. This leads to the occurrence of defects in the wiring. According to the application domain, the defects of cables may have catastrophic consequence [2]. In this area, reliability becomes a safety issue.

There are several emerging technologies that may help to locate and characterize faults wires. The most widely used technique for fault location in automobile wiring is reflectometry [2]. It is based on the same principle that radar. A high frequency electrical signal is sent down the wire, where it reflects from any impedance discontinuity such as open or short circuits. The difference (time delay or phase shift) between the incident and reflected signal is used to locate the fault on the wire. The nature of the input signal is used to classify each type of reflectometry: Time Domain Reflectometry (TDR) uses a fast rise time pulse [3], Frequency Domain Reflectometry (FDR) uses a sine wave signal [4], Sequence Time Domain Reflectometry (STDR) a pseudo-noise (PN) code, and Spread Sequence Time Domain Reflectometry (SSTDR) a sine-wave-modulated PN code [5]. These last two techniques can test wire in live. Also a new method called, Time-Frequency Domain Reflectometry (TFDR) was presented in [6]. All these methods present some limitations to characterize the impedance of the fault as well as the position in some case of wire.

The reflectometry response is not self-sufficient to solve the branched wiring problem. There exists a need for the development of specific methods to be integrated with the reflectometry response to characterize and locate faults in branched networks. Different methods have been proposed. In a baseline method the response of the faulty network is compared with either the pre-measured or simulated response of its (known) healthy condition. In [7] the technique proposed by the authors allow to identify and localize of small detects in simple cable based on the post-processing of the frequency domain (FDR) measured result by wavelet analysis application. In [8] Time domain signal restoration and parameter reconstruction of a simple nonuniform RLCG transmission line is performed using the wave-splitting technique and the compact Green functions technique. It reconstructs the transmission lines parameters.

Wiring networks can be affected with two types of faults: “soft ones” are created by the change of the impedance along the line due to simple deformation in the wire [9]. “Hard faults” are open and short circuits. For the first type of faults, the reflectometry response of the faulty network presents a simple deviation or variation versus the impedance of the fault, in the defects location. In the case of hard faults the structure of network as well as the response changes.

In this paper we propose a novel and efficient method to locate and characterize the defects in the faulty wiring network using the reflectometry response and genetic algorithms. In the case of soft fault the physical parameters of the defects are reconstructed as well the position. For the hard one the structure of the faulty wiring network is reconstructed. A direct model describes the propagation of the wave along the lines using a numerical method. Then a genetic algorithm is used to solve the inverse problem minimizing the error between the reflectometry response and the response given by the direct model. In section II the forward model and its numerical counterpart (Finite Difference Time Domain (FDTD) method) are described and applied to model the propagation of a signal in simple wire and wiring network. In section III the TDR response is simulated and compared with real measurements. In section IV the proposed method for the reconstruction of the physical parameters and network structure using a genetic algorithm is described and its ability is illustrated with two examples.

II. Numerical model for simple and complex wires

A. Propagation Model

The propagation in a transmission line can be modelled by a RLCG circuit model [10]. This model is valid for an infinitesimal length of the line, provided that the length of the transmission line is less or equal than tenth of the guided wavelength, figure 1. The quantities R (resistance), L (inductance), C (capacitance) and G (conductance) are the electrical parameters per-unit-length are computed with a 2D finite element approach. Most of the transmission lines can be assumed to be lossless, and hence the parameters R and G are zero or small enough to be neglected.

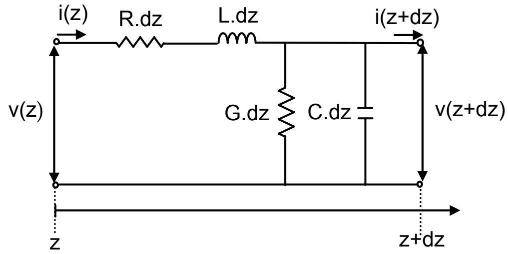

Fig.1. Equivalent circuit of a differential length dz of a two-conductor transmission line.

A finite length of transmission line can be represented as a cascade of sections of the form of figure 1. Applying the laws of circuit (Kirchhoff's low) and taking the limit as dz→0 leads to the following differential equations:

(1) $$\frac{\partial v(z,t)}{\partial z} = R.i(z,t) - L.\frac{\partial i(z,t)}{\partial t}$$

(2) $$\frac{\partial i(z,t)}{\partial z} = G.v(z,t) - C.\frac{\partial v(z,t)}{\partial t}$$

The system of differential equations (1) and (2) in space (z) and time (t) describes the evolution of voltage v and current i along the transmission line in function of the different parameters of the line. The Finite Difference Time Domain (FDTD) method is a simple and intuitive electromagnetic modeling technique [11] which converts the differential equations system into a finite difference equations system. This leads, in the lossless case, to :

(3) $$V^{n+1}(z) = \frac{dt}{C}.\frac{I^{n+1/2}(z+1/2) - I^{n+1/2}(z-1/2)}{dz} + V^{n}(z)$$

(4) $$I^{n+1/2}(z+1/2) = \frac{dt}{L}.\frac{V^{n}(z+1) - V^{n}(z)}{dz} + I^{n-1/2}(z+1/2)$$

The spatial and time increments (dz and dt) are chosen to satisfy the "domain of dependence condition" or "Courant-Friedrichs-Lewy condition" [11]. In this work the length of the grid cell size dz is chosen to be small compared to the wavelength of the source λ_{min} signal, generally on the order of dz = $\lambda_{min}/60$. The sampling interval dt chosen in the study is given by dt =dz/2.c, where c is the velocity of propagation of the wire with 0.5 c_0 < c < 0.8 c_0, c_0 being the speed of light. This choice insures the stability of the time stepping algorithm.

B. Network Analysis

The analysis of the single wires is very important but in a real automobile or aircraft environment all the wirings are part of branched wiring networks and the faults must be analyzed as part of these networks. The FDTD method provides the suitable solution for such analysis. To model networks, transmission conditions have to be implemented at the junctions. The reflection coefficient at a junction or termination can be evaluated using equation (5), where Z_0 is the characteristic impedance of the cables and Z is the impedance at the mismatch. The quantities $V_{reflected}$ and $V_{incident}$ are the reflected and incident waves respectively.

(5) $$\Gamma = \frac{V_{reflected}}{V_{incident}} = \frac{Z - Z_0}{Z + Z_0}$$

The value of Z is equal to 0 for a short ended termination and is equal to an infinitely large value for an open ended termination. For a junction, the value of Z depends on the number of branches at the junction. If the lines are of equal impedance, this value will be equal to Z_0/n (parallel combination of electrical lines) where n is the number of branches present at the junction. Equation (6) gives the relationship between the reflection coefficient at a junction and the number of branches present at that junction.

(6) $$\Gamma = \frac{Z_0 - \frac{Z_0}{n}}{Z_0 + \frac{Z_0}{n}} = \frac{n-1}{n+1}$$

When the lines are of unequal impedances, equation (6) is no more valid to determine the number of branches at a junction. The value of Z in these cases should be evaluated by taking the individual impedances into consideration. The complexity of this problem increases when increasing the number of stages in the network.

III. Reflectometry for complex network topology

In this section the FDTD method is used to simulate time domain reflectometry responses in two different configurations in order to validate the propagation model.

A first comparison between numerical results and real measurements is performed for a complex network made of KW22A coaxial cable (figure 2). The network includes six branches. The type of termination of the branches is indicated at the end of the branch. A Raised Cosine Pulse [12] was used as a source signal:

(7) $$e(t) = \begin{cases} 0.5*(1-\cos(2*\pi*F*t) & 0 < t < 1/F \\ 0 & \textbf{Otherwise} \end{cases}$$

where F is the pulse frequency.
The rising time is 4 ns, and the voltage at high state is 1volt. The impulse response is deduced from measurement of S11 parameter with a Vector Network Analyser (VNA) in frequency domain from 300 kHz to 500 MHz, connecting the ports of the VNA to line number 1 [13].

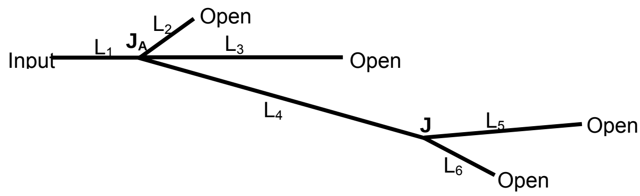

Fig.2. Studied network topology; L_1= 1 m, L_2= 0.60 m, L_3= 2.25 m, L_4= 4.25 m, L_5= 1.75m and L_6= 1 m.

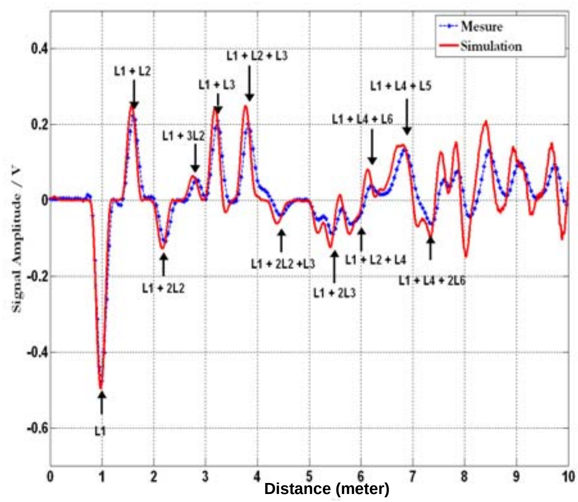

Fig.3. Comparison between simulation results and measures for the TDR response

In Figure 3 the position and magnitude of the peaks are due to the location and change in impedance along the wire. In reality, the raw data is actually given as a time delay rather than a distance knowing that the distance is nothing but the velocity of propagation divided by the time delay. For sake of simplicity the distances have been divided by two to be related with the physical length of the lines. Figure 3 illustrates a good agreement between measures and simulation results, both for positions and amplitudes of the main peaks. The difference between the simulated and measured values may be due to variation between the ideal and actual characteristic impedance of the cable, and also to the impedance of the connection that was not accounted for in the model.

In the second configuration the analysis of the faulty wiring network are studies. The figure 4 show the network includes only one defect (or open or short circuit damage) at 6 meters from the input and located on the branch with length 1.75 meters. The reflectometry response for the different faults is compared with the response of its healthier version, figure 5. The signature at the fault location is blow up for better observation in the small box on the left. Reflexion other than open and short circuit are small. They are so small that are not easily seen on the original graph.

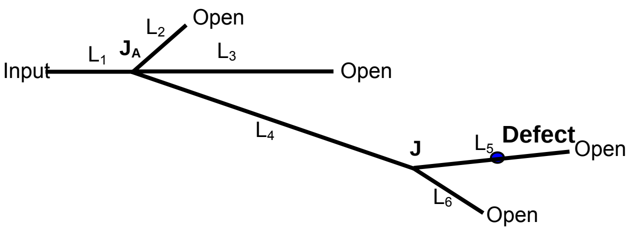

Fig.4. Complex network topology with one fault; L_1= 1 m, L_2= 0.60 m, L_3= 2.25 m, L_4= 4.25 m, L_5= 1.75m and L_6= 1 m.

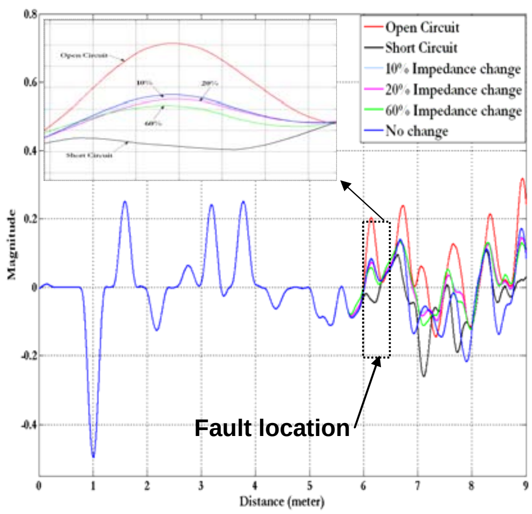

Fig.5. Reflectometry Response for the different faults compared with the response of its healthier version.

IV Inverse problem

A. Solving the inverse problem by Genetic Algorithm

Genetic Algorithms (GAs) are global optimization methods based on genetic recombination and evolution in nature [14]. GAs uses an approach that commonly involves starting with a random selection of design space points of M populations. The system is discretized into P parameters in a model vector m called a chromosome. Each parameter m_j, j =1… P, is called a gene in accordance with the natural terminology of the genetic theory. A gene is a binary encoding of a parameter

$$(8) \qquad \mathbf{m_j} = \mathbf{m_j^{min}} + \frac{(\mathbf{m_j^{max}} - \mathbf{m_j^{max}})}{2^{\mathbf{n}} - 1} \cdot \sum_{\mathbf{i}=0}^{\mathbf{n-1}} \mathbf{b_i} 2^{\mathbf{i}}$$

The parameter m_j represents either the length of the branch L_i, or the inductance L and capacitance C, or the position N_d of the faults. The set of values b_1, b_2… b_{n-1} is the n-bit string of the binary representation of m_j, and m_j^{min} and m_j^{max} are the minimum and maximum values admissible for m_j, respectively. Using a sufficient number of bits per parameter provides a fine-grained set of values.

The genes of these initial individuals are combined in meaningful ways to produce new solutions, and these are evaluated and ranked by an objective function value [14]. Finally, the GA iteratively generates a new population, which is derived from the previous population through the application of the genetic operations; selection, mutation and crossing each operation are controlled with probability; P_s, P_m, and P_c respectively, that allow the algorithm to explore new regions of the problem space. The new population will contain increasingly better chromosomes (best individuals or parameters) and will eventually converge to an optimal population that consists of the optimal chromosomes.

The role of the selection is to select individuals in the population from their fitness. The crossover operation randomly takes a pair of chromosomes at the same position, and creates an offspring chromosome by recombining the alternate portions of the parent individuals. The mutation implies small random changes to one or several of the genes in a chromosome in order to promote variation and diversity in the population.

In our problem, both the reflectometry response (measured or simulated) and the direct model are used to reconstruct the wiring network. The parameters are the lengths of the different branches L_i. From the reflectometry data of the wiring network under test, the methodology of reconstruction leads to the resolution of an inverse problem: GA's are used to minimize the objective function *F(v)* given by (9), where $v^{TDR}(t)$ is the given initial impulse response and $v^{Mod}(t)$ the response given by the direct model.

$$(9) \qquad \mathbf{F(v)} = [\frac{1}{\mathbf{N_{stop}}} \int_0^{\mathbf{T}} \frac{\left|\mathbf{v^{TDR}(t)} - \mathbf{v^{Mod}(t)}\right|^2}{\left|\mathbf{v^{TDR}(t)}\right|^2} \mathbf{dt}]^{1/2}$$

B. Numerical results

By numerical simulation, the performance of the proposed method for identification, location of soft fault and the reconstruction of a wiring network affected with a hard fault are illustrated. The reflectometry response used as the input is obtained from measurements or simulated values.

Two configurations have been studied. In a first one a wiring network affected with one soft fault is considered. The second one involves the networks affected by open or short circuits.

Example 1

The performance of the proposed inversion algorithm was checked to characterize and localize faults in faulty networks from the reflectometry response.

Let us consider the faulty wiring network as shown in figure 4. The network constituted with a twin lead wire (Z_0=87.63 Ohm) is affected only in one branch with faults having a change in impedance on the order of 10% = 86.49 Ohm, 20% = 94.35 Ohm and 60% = 125.8 Ohm. The search range for the unknown impedance Z_{Fault} is chosen to be fom 20 to 200 ohms. The position N_d extends from $N_{d(min)}$ = 0.01m to $N_{d(max)}$ = L_5 = 1.75m, representing the minimum and maximum of each branch in the network structure. The branch where the fault occurs is assumed to be known. In this case the number of parameters is limited to three (C_{Fault}, L_{Fault} ; impedance and N_d the location). But the generalization of the methodology for the entire faulty wiring network is possible by increasing the number of the parameters to be searched. For this problem the following parameters have been used : population size M = 150, probability of crossover P_c=70%, probability of mutation P_m=1.5%. The binary string length is set to be 7 bits. The optimization process converges within 100 iterations. The input of the algorithm is $v^{TDR}(t)$, the reflectometry response shown in figure 5. The genetic algorithm parameters and the result obtained for the different faults are shown in table 1.

	GA parameters			Results	
	Bits	P_m	P_c	Impedance (Ohms)	Location (meter)
10% Impedance Change 86.49 Ohm				**85.52**	**1.96**
20% Impedance Change 94.35 Ohm	**7**	**1.5%**	**70%**	**96.13**	**2.03**
60% Impedance Change 125.8 Ohm				**124.25**	**1.91**

Table 1. Genetic algorithms parameters and numerical results

The results are satisfactory : the impedances of the defects are close to those of the defaults value. Also the positions are correctly recovered.

Example 2

In this second example the network is affected by hard faults. In a first configuration the proposed method is applied for a healthy network. The TDR measure (figure 3) is the input of the algorithm for the reconstruction. Figure 6 show the results of the method: the reconstructed wiring network is very similar to the original structure. Figure 7 compares the reflectometry response of the healthy network (measurement data) and the reconstructed one.

In this case the optimised parameters are the lengths of the different branches of the network.

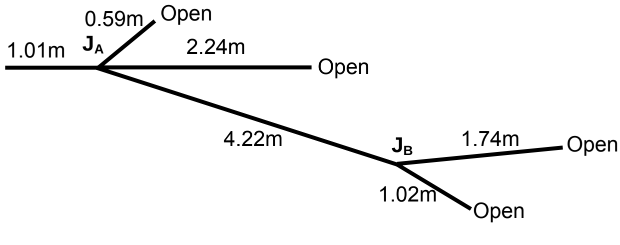

Fig.6. Network reconstructed from measurement data

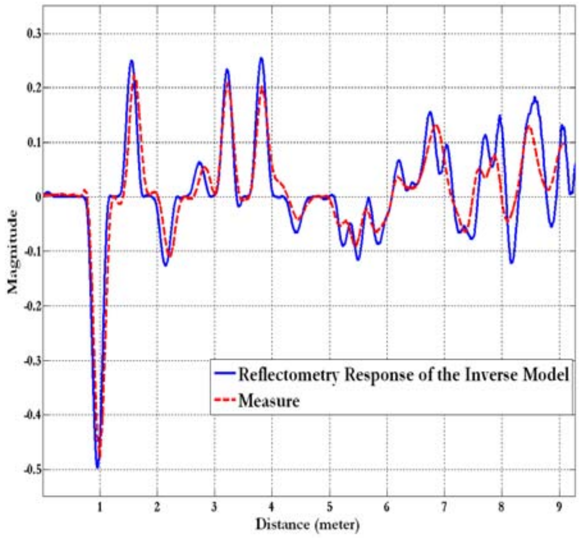

Fig.7. Comparison between the reflectometry responses of the network reconstructed with GA with the healthy version

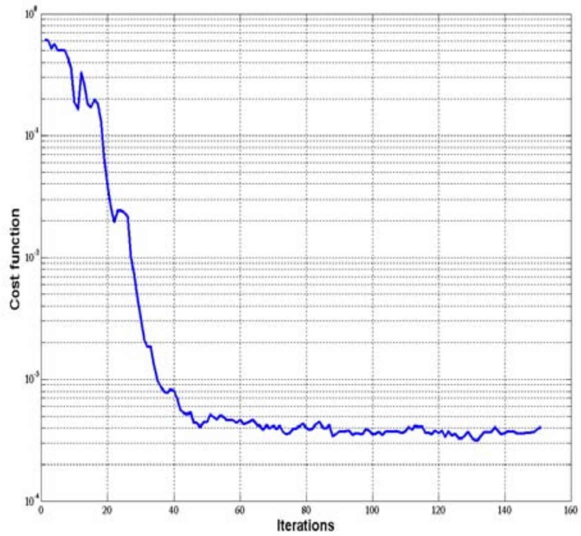

Fig.8. Cost function, ΔL =4mm, Bits = 7, Iterations = 150, Population size = 130, P_c = 60%, P_m= 1.5%

In a second configuration the reconstruction of a wiring network affected by a hard fault is considered. We use as input of the algorithm the reflectometry response of the network shown in figure 4. This response is obtained using a frequency model based on standard microwave propagation theory [13]. The new wiring network reconstructed affected with an open circuit is illustrated in figure 9 and 10 respectively. The methodology allows localizing the defects on the branches of the network.

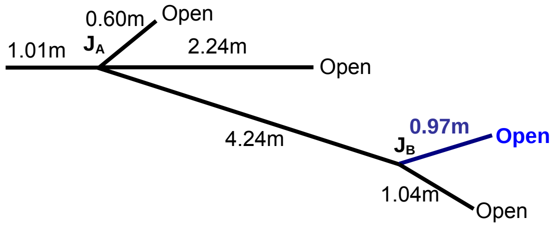

Fig.9. Network reconstructed from reflectometry response of CEA model, localized open circuit fault

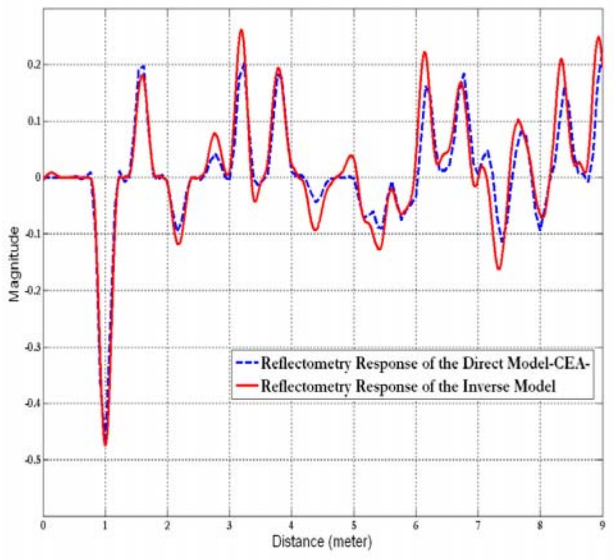

Fig.10. Comparison of the reflectometry response of direct and inverse model in case of open circuit fault.

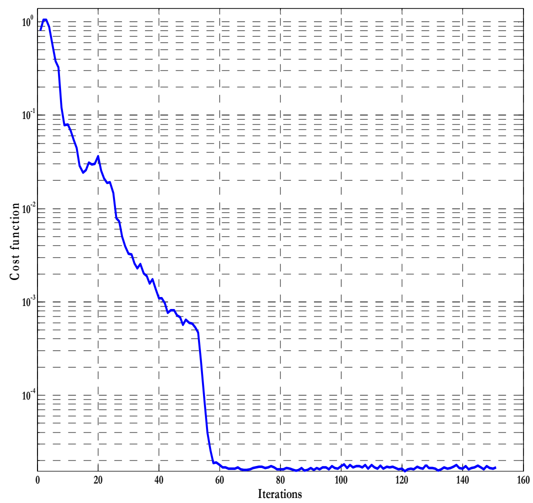

Fig.11. Cost function, ΔL =4mm, Bits = 7, Iterations = 150, Population size = 130, P_c = 60%, P_m= 1.5%

V. Conclusion

This paper describes an inverse procedure dedicated to time domain reflectometry for the localization and characterization of defects in simple wires and faulty wiring networks. Two complementary steps were addressed. In a first step a direct model was proposed to simulate the wave propagation using RLCG circuit parameters and FDTD method in order to retrieve the response from the network under test. In the second step, the inverse problem is solved by minimizing the error between the given reflectometry response and the response of the direct model. This inverse problem was solved with genetic algorithms. Two types of defects have been studies. For the first one (soft defect), the location and reconstruction of physical parameters have been performed. For the second one (hard fault), the reconstruction of the faulty wiring network has been illustrated. The approach was tested with experimental data and demonstrated to be effective for the localization and characterization of defects. From this work it can be pointed out that the main difficulties in applying the GA is to choose the parameters. One of the main limitations of the algorithm remains the assumption relevant to the knowledge of the structure. This limits the research area when solving the inverse problem.

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