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PERFORMANCES OF DIFFERENTIAL EVOLUTION TO OPTIMIZE ULTRASONIC
ARRAYS TRANSDUCERS

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ABSTRACT

The design of an ultrasonic array and its settings for a specific inspection involves multiple parameters: number and arrangement of elements, frequency, etc. A compromise between requirements (e.g. beam characteristics) and limitations (e.g. number of elements) is often sought via parametric studies based on simulation tools to ensure that the transducer has suitable performances in terms of detection of the defects envisaged. An automatic optimization method, based on an evolutionary algorithm and numerical simulation, has been proposed and adapted to meet the specificities of the non-destructive testing applications. The performances of the method are evaluated for two cases of applications: (i) evaluating the influence of the different tuning parameters, and (ii) comparing the results by defining two or three objective functions to optimize the same problem.

Keywords: Ultrasonic, Array, Optimization, Simulation, Transducer

PACS: 43.38.Hz, 43.35.Zc, 02.60.Pn

INTRODUCTION

Phased-array techniques enlarge the capabilities of transducers in terms of coverage, sensitivity and imaging. However, it also increases the complexity of the design (number and arrangement of elements) and the definition of the inspection setup (T-R functionalities, electronic delays, etc.). Nowadays, industry is interested to design phased-array transducers for ultrasonic non-destructive testing (UT) that guarantee a good quality of the beam (prescribed beam dimensions, avoiding grating lobes) and a reduction of costs (minimization of the number of elements). When these two goals are conflicting, an optimization has to be performed to converge onto the most convenient solution. Up to now, this has been carried out by computational parametric studies, which can be time-consuming, tedious, and somehow delicate.

An optimization method based on the so-called Randomized Adaptive Differential Evolution (RADE) [2] and connected to the ultrasonic module of CIVA [3-4] has recently been proposed [1]. The motivation of the present work is to evaluate the performances of this method. The next section summarizes this optimization method. The two following ones describe two cases of application that are used to evaluate its performances. The first one concerns the optimization of the positioning of an array on a nozzle and of the applied electronic

delays. It is processed for different values of tuning parameters of the RADE. The second one concerns the design and the set-up of an array for the inner inspection of a pipe. It is processed as a multi-objective problem by defining two then three objective functions. A brief conclusion ends this paper.

OPTIMIZATION

Optimization problem

The form used to describe a constrained multi-objective optimization problem is:

$$\begin{aligned} \text{Minimize} & \quad f_l(\mathbf{X}) & \quad l = 1, \dots, N_o \\ \text{Subject to} & \quad g_m(\mathbf{X}) < 0 & \quad m = 1, \dots, N_c \\ & \quad x_j^l < x_j < x_j^u & \quad j = 1, \dots, N \end{aligned} \quad (1)$$

The vector $\mathbf{X} = [x_1; \dots; x_N]$ is a candidate solution. The N_o objective functions f_l are representative of the problem at hand. The N_c constraint functions g_m are inequalities that need to be satisfied by the optimal solution(s). The vectors $\mathbf{X}^l = [x_1^l; \dots; x_N^l]$ and $\mathbf{X}^u = [x_1^u; \dots; x_N^u]$ are respectively the lower and upper bounds of the search range. Since RADE is able to solve only unconstrained mono-objective problems, extensions are proposed next to handle constraints, precisions, and multi-objective strategies.

Randomized Adaptive Differential Evolution (RADE)

This algorithm is derived from Differential Evolution [5] with auto-regulation of the mutation factor. First, the population is initialized by a uniform distribution in the search domain. Then, it uses iteratively operators (mutation, crossover and selection) to evolve a population of *NP* candidate solutions in order to converge toward an optimum. This evolution is performed for a given number of generations (k_{max}).

The practical approach to solve NDT problems is synthesized in Fig. 1. The first step is to extract useful information from this problem in order to: (i) model the problem in the simulation software; (ii) identify the variables of the optimization, define their research domain and, if necessary, their precision; (iii) choose the values for the tuning parameters of the RADE (*Cr* and *NP*). High values of *NP*, the population size, will improve the robustness but also increase the time of computation. Small values of *Cr*, the crossover rate, will lead to perturb few variables at the same time. This latest has less weight on the robustness but can influence the convergence speed.

Extensions

Two kinds of constraints are considered. The first keeps the variables in the research domain. The second ones are inequalities that involve several variables, and which have to be satisfied by the optimal solution.

Because RADE had been designed to solve real-variables problems, the precision handling [1] has been developed to take into account a precision step beyond which the solution is of no use to the end-user. In brief, computation time is saved since solutions too close to one another are not computed; and the optimal solution found makes sense, from the design point of view, since it has no useless digits.

The main difficulty faced with multi-objective problems is that two solutions cannot be easily compared. The so-called non-dominated sorting [6] has been implemented. It is based on the dominance relation:

$$X_1 \text{ dominates } X_2 \Leftrightarrow \forall l \in [1, N_o], f_l(X_1) \leq f_l(X_2) \text{ and } F(X_1) \neq F(X_2) \quad (2)$$

where $F(X) = [f_1(X), \dots, f_{N_o}(X)]$. In a population, the set of non-dominated solutions is called Pareto-optimal set. By

favoring these solutions, the RADE is able to treat such problems.

INFLUENCE OF TUNING PARAMETERS

UT Application

These algorithms have been tested on a nozzle inspection [1] to optimize the detection of planar flaws using an 8x8 flexible array operating at 2 MHz. The sought defects are on the inner surface, at the junction of the two pipes, and oriented radially relatively to the secondary pipe as depicted in Fig. 2(a). The objective of the optimization is to find both the position of the array (Y, α and Θ) and of the focusing point introduced in the computation of the delays (τ, θ, φ) that maximize the amplitude of the corner echo. The problem is not obvious since this amplitude depends on both the deviation of the beam and on the angle of incidence on the defect. A manual optimization study had been previously performed by an expert for the angular positions $\Theta = 0^\circ$ of the defect. Solutions given by the presently proposed method can be compared to this “expert” solution.

Performances

To observe the influence of the tuning parameters (precision, *NP* and *Cr*) on the resolution of this problem, several optimizations are performed. The set proposed in [1] (use of precision, *NP* = 20 and *Cr* = 0.7) is used as a reference and each parameter is modified individually. Fig. 2(b) compares the evolution of the amplitude of the best solution when a precision is defined and when it is not. The amplitudes displayed are given in decibels, the 0 dB level being the “expert” solution. The precision handling significantly reduces the number of generations, and therefore the corresponding computation time required, in order to reach the optimized solution: 33 generations vs. 50 generations. The Fig. 2(c) displays the evolution of the amplitude of the best solutions for three values of *NP*. For *NP* = 12, the population seems too small and prematurely converges to a solution that is not optimal. For *NP* = 60, the population converges slowly to the optimum, and still does not reach the optimum after 3030 evaluations of candidate solutions. Fig. 2(d) compares the evolution of the amplitude of the best solutions using four

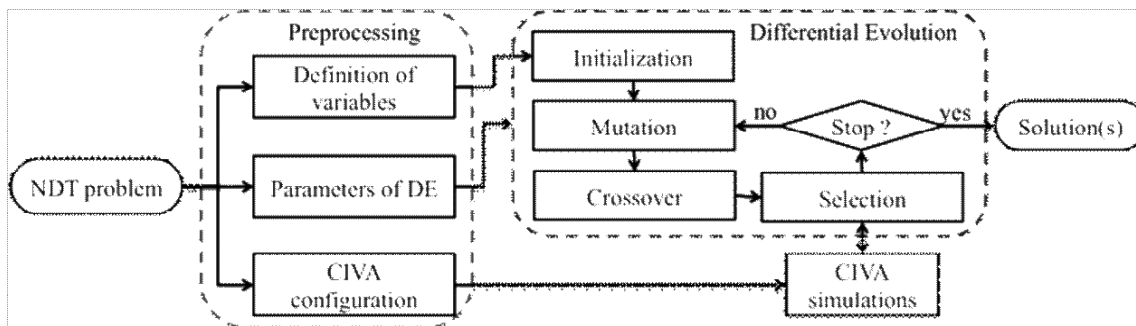


Fig. 1 : Flowchart of the proposed approach of using optimization to solve NDT problems.

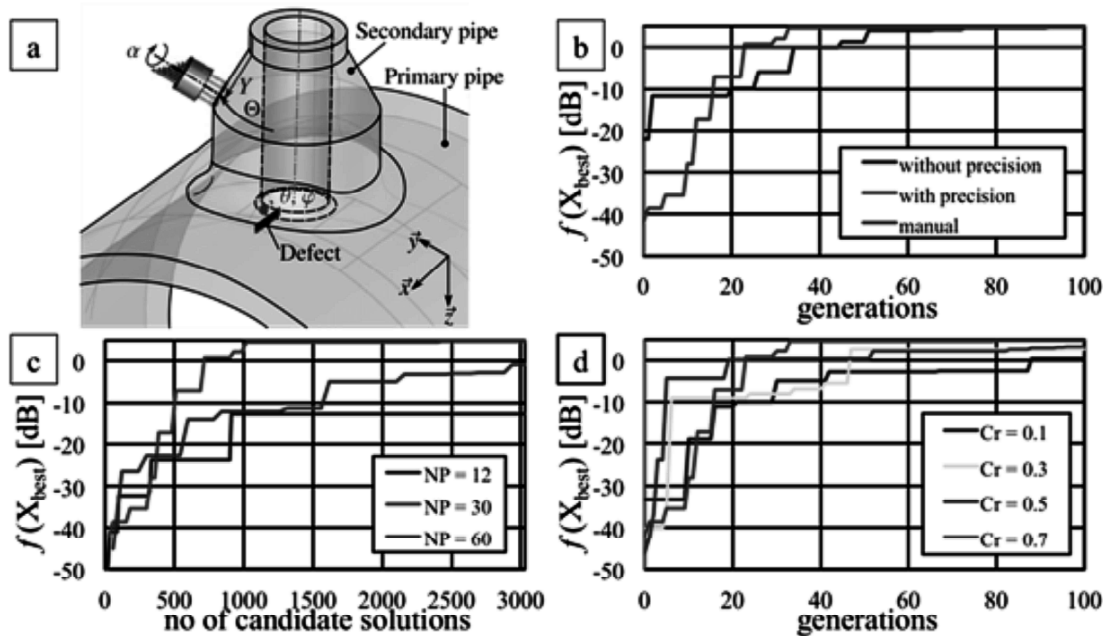


Fig. 2 : Optimization of a nozzle inspection. (a) Inspection set-up and definition of variables. Evolution of the best solutions amplitude (b) with and without precision handling, (c) for $NP = 12, 30$ and 60 , and (d) for $Cr = 0.1, 0.3, 0.5$ and 0.7 . Values of the amplitude are given in dB by comparison to the manual solution.

values of Cr (0.1, 0.3, 0.5 and 0.7). The influence of this parameter is not so obvious. Nevertheless, the convergence seems to be faster for the highest values of Cr . These results are in accordance with the influence of the tuning parameters considered in the optimization section of this paper.

INFLUENCE OF THE NUMBER OF OBJECTIVE FUNCTIONS

UT application

The second example concerns the inner inspection by a surrounded array of a stainless steel pipe [1], filled by water,

to detect cracks oriented along the pipe axis using 45° compressional waves, as depicted in Fig. 3(a). The section of the pipe is inspected by electronic commutation. The problem is to define the array (dimensions, arrangement and central frequency of the elements), the dimension of the commuting aperture, and the angular deviation of the electronic delays. The number of available channels is fixed at 256, which constrains the number of elements. The objective is to guarantee the good characteristics of the beam: (i) direction (45° on the defect), (ii) focalization on the outer surface, and (iii) to minimize grating-lobes. The evaluation of candidate solutions is based on the simulation by CIVA of the ultrasonic beams radiated by the array (sketched in Fig. 3(b)).

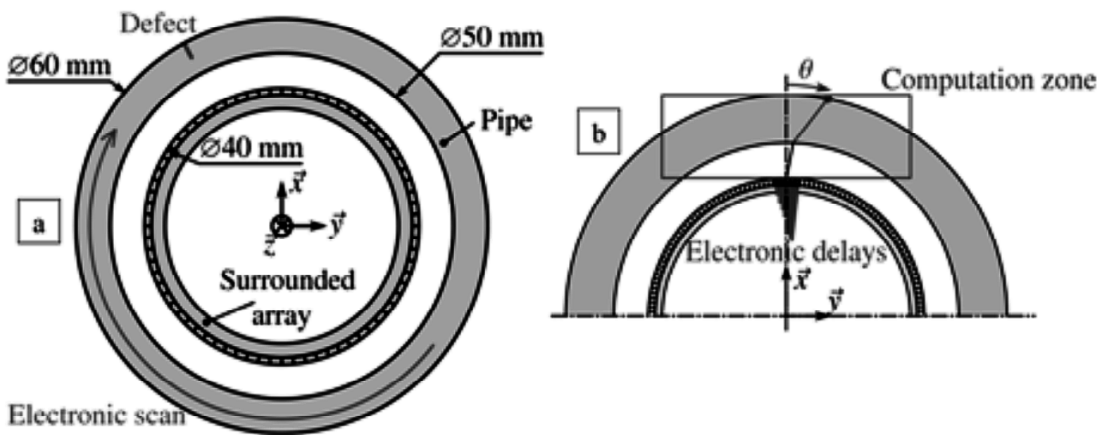


Fig. 3 : (a) Schematic view of the pipe inspection problem. (b) Sketch of the computation zone and the array setting. The electronic delays applied to the rotating active aperture are plotted in red.

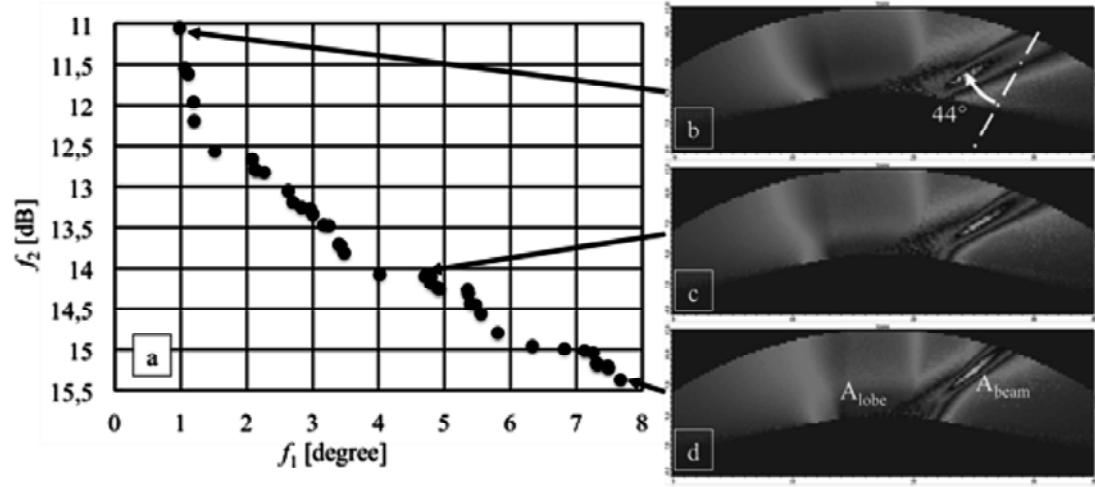


Fig. 4 : (a) Pareto-optimal sets obtained at generation 50 for all solutions for which $f_1(X) < 8^\circ$. Maps of the ultrasonic elds computed for the three solutions: (b) the solution with best beam deviation, (c) the median solution, and (d) the solution with best beam-to-grating-lobe ratio.

Processing with two objectives

This problem is first optimized using two objective functions: f_1 ensures a beam orientation as close as possible to 45° on the defect, and f_2 aims at maximizing the beam amplitude with respect to the grating lobe amplitude. Beam depth is taken into account in f_2 using a weighting coefficient. The following values of tuning parameters have been used to perform this optimization: $Cr = 0.7$, $NP = 25$, $k_{max} = 50$. At the last generation, the Pareto-optimal set is composed of 94 solutions corresponding to different compromises between f_1 and f_2 . The solutions of this set for which $f_1(X) < 8^\circ$ are displayed in Fig. 4(a) in the objective domain. The three variables mostly affecting the compromise are the number of elements in the active aperture, the frequency, and the deviation angle θ .

Fig. 4(b-c-d) give the computed elds of three representative solutions of the Pareto-optimal set. Solution (b) favors the beam orientation while solution (d) improves the beam-to-grating lobe ratio, with solution (c) being an intermediate solution. This illustrates the interest of multi-objective optimization that is generally used when one solution, which optimizes all objectives at the same time, cannot be found. The work is much reduced since it consists of only choosing the best compromise but not to nd optimized solutions.

Processing three objectives

In a second time, the problem is optimized using three objective functions: f'_1 is identical to f_1 , f'_2 aims at maximizing the beam amplitude with respect to the grating lobe amplitude, and f'_3

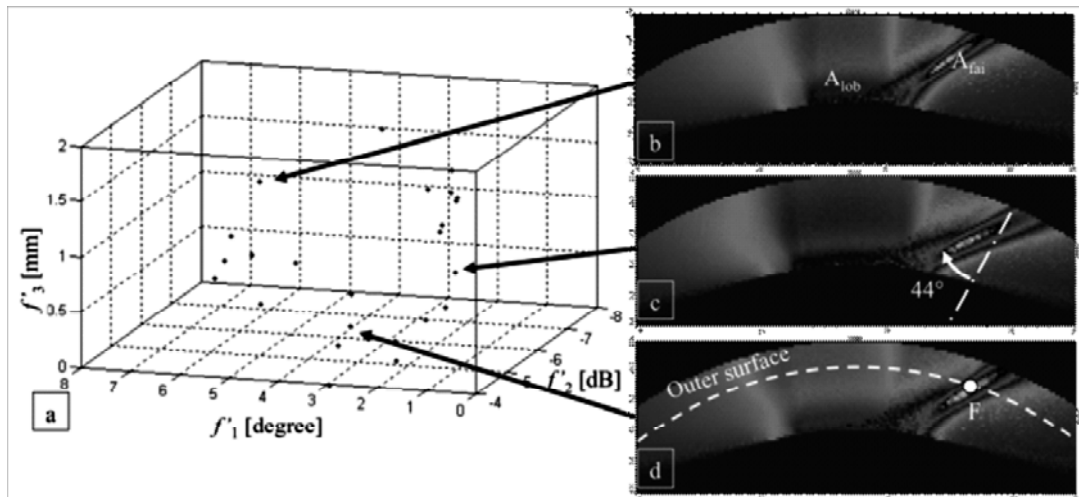


Fig. 5 : (a) Pareto-optimal sets obtained at generation 50 for all solutions for which $f_1(X) < 8^\circ$ and $f'_3(X) < 2$. Maps of the ultrasonic elds computed for the three solutions: (b) the solution with the best beam-to-grating-lobe ratio, (c) the solution with the best beam deviation, and (d) the solution with the best beam depth.

ensures that the beam is as close as possible to the outer surface. The tuning parameters are the same. At generation 50, the Pareto-optimal set is composed of 89 solutions, which are identical or very close to the ones found previously with two objectives. The solutions of this set for which $f_1(X) < 8^\circ$ and $f_2(X) < 2$ are displayed in Fig. 5(a) in the objective domain. Fig. 5(b-c-d) give the computed elds of three representative solutions of the Pareto-optimal set. The solution (b) favors the beam-to-grating lobe ratio while solution (c) favors the beam orientation, and solution (d) improves the focalization on the outer surface. Therefore, the two approaches give very similar results. However, this second optimization shows that the interpretation of the Pareto-optimal set is less convenient with three objectives than with two.

CONCLUSION

A method based on the use of a Differential Evolution has been proposed to optimize the array design and setting. The algorithm is implemented and connected to the ultrasonic simulation modules of the CIVA software platform. The performances of the method are evaluated for two realistic cases. Firstly, these tests underline the influence of the values of the tuning parameters. Secondly, they show that increasing the number of objective functions makes the interpretation

less easy. Lastly, with a meticulous definition, two objectives can sometime be defined as one and give very similar results.

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