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A Preliminary Study of Multi-Parameter POD Curves for a Guided Waves Based SHM Approach to Lightweight Materials

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Abstract. In view of an extensive literature about guided waves propagation, interaction and numerical simulation in plate-like structures made of metallic and composite materials, a lack of information is pointed out regarding their reliability in structural health monitoring approaches. Typically, because of uncertainties in the inspection process, the capability of non-destructive testing systems is expressed by means of suitable probability of detection curves. Based on Berens' model, a linear relationship is established between probability of detection and flaw size. Although the uncertain factors differ from a non-destructive inspection technique and a structural health monitoring approach, the same mathematical framework can be assumed. Hence, the authors investigated the application of a recently developed non-destructive testing Multi-Parameter POD approach to a guided waves based SHM one: numerical simulations as well as experimental data from flawed plates were combined to bring about a "master" POD curve. Once established, it can be used to build the POD curves of the single key factors as flaw size, orientation, structural attenuation and so on.

INTRODUCTION

Typically, non-destructive testing (NDT) capability is expressed, according to Berens' model [1], by means of "Probability of Detection" (POD) curves, where the probability of detection is a function of flaw size. As significant outputs, the upper confidence bound and the $d_{90/95}$ parameter (identifying the flaw size that can be detected with a probability of 90% and a confidence of 95%) define the system capability. Here, the typical variability sources, involved in the measured outcome, are human factors (deeply studied by Bertovic [2]), flaw morphology, acousto-elastic properties of the medium [3-5] and so on, as illustrated in Fig. 1. Differently, a structural health monitoring (SHM) system deals with sensor networks permanently installed on a host structure and its POD will change as a function of time due to ageing effects, environmental factors, etc. Moreover, the setup and installation of the sensors is, today, not a consistent procedure and thus subjected to other sources of variability. Thus, a complete POD curve mainly based on experimental data is an awesome task. Taking advantage of reliable numerical models, recently Muller and Aldrin [7, 8] proposed Model-Assisted POD approaches able of simulating the variability involved in a SHM approach, although numerical efforts and computational times can be prohibitive [9].

In this study, the authors investigated the application of a Multi-Parameter POD [5] approach with the aim to analyze the sensitivity of a SHM system based onto a PZT sensors network. Different key factors, like the surface mounting process (not reproducible), piezo-electric constants, flaw morphology and orientation with respect to PZT network, contribute to define the variability of the process and a simple approach like Berens' one cannot be applied any longer since it states a linearity of the response against one independent variable. Thus, numerical and experimental data can be combined to establish a "master" POD curve by means of which the dependence on any single factor can be established.

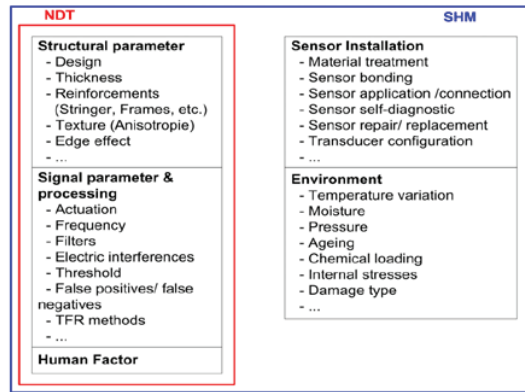


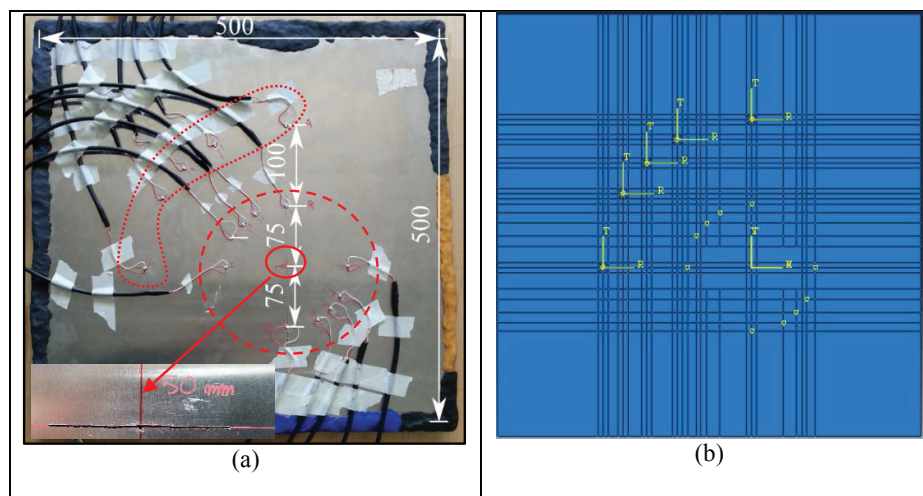
FIGURE 1. Variability factors influencing NDT and SHM [6].

GUIDED WAVES EXPERIMENTAL AND NUMERICAL RESPONSE

Two Al-5083 plates, whose dimensions are 500x500 mm² with a thickness of 2 mm, were instrumented using a network of circular 5 mm diameter and 1 mm thickness PZT transducers (PIC-255), as reported in Fig. 2 (a). An artificial slot was established as representative of a defect and its dimension was gradually increased up to 100mm; its position, highlighted with a red circle in Fig. 2 (a), reflects consideration regarding reflections from boundary conditions and pulse length that can mask the valuable response. Considering the location of transducers, the outer ring, highlighted by a red dotted line in Fig. 2(a), dealt with piezo-actuators, whereas the rings nearby the flawed area (red dashed line) gave out Pulse-Echo (PE) and Pitch-Catch (PC) responses. Moreover, the setup allowed different strategies of actuation and reception as in Fig. 2 (c), (d).

The well-known mode tuning effects due to the coupling between the host structure and PZT elements, matched with an out-of-phase and an in-phase way of actuation [10, 11], are combined in order to selectively enhance a specific A₀ or S₀ wave mode [12]. Hence, a Hanning windowed 3.5 cycles tone burst, 100 V_{peak-peak}, was used with central frequencies equal to 50 and 280 kHz respectively for the anti-symmetrical and symmetrical fundamental modes.

Since SHM relies on comparisons of different states (pristine-damaged configuration), a baseline signal immediately after the installation of the PZT network is acquired as the reference condition for PE and PC response. To quantify the response, reflection and transmission coefficients are expressed dividing the value of the reflected or transmitted wave peak by that of the incident wave peak, after applying the Hilbert transform (HT) to their respective CWT scale coefficients. Concerning numerical responses, finite element analyses were carried out using an explicit dynamic formulation by ABAQUS CAE 6.13.1 [13], but excluding, as a first approximation, the multi-physics behavior due to electro-mechanical coupling effects of PZT and host structure; actuation is simulated applying in-plane radial displacement on the peripheral nodes of PZT diameter. The employed mesh used eight node linear elements with reduced integration (C3D8R), whose plane dimension is 2 mm and with an aspect ratio of two, allowing two elements along the thickness. Time integration step was set to 50e-9 s. As previously stated, although computationally efficient, the explicit dynamic simulation in ABAQUS cannot support piezo-elements, thus a direct comparison of the data (mV from experiments and amplitudes from FEA) was impossible. As a numerical output, the out-of-plane displacement U₃ was then assumed.



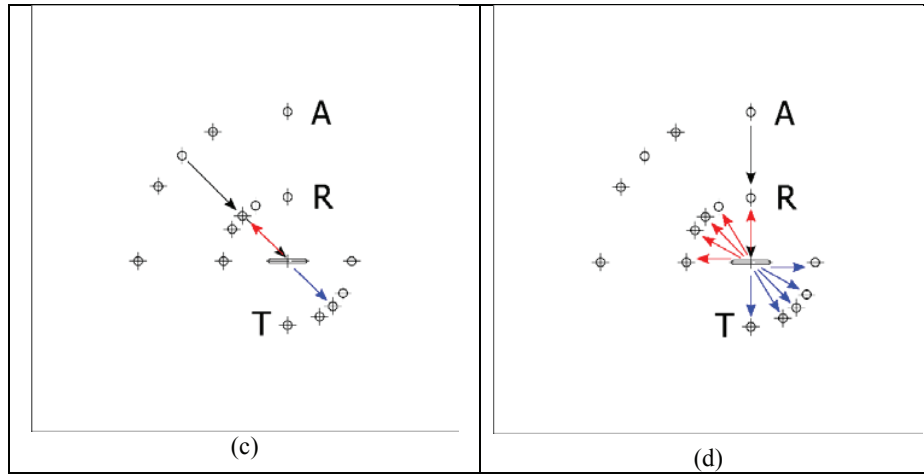


FIGURE 2. (a) Detail of the sensor network equipped plate, (b) FEM model, (c) and (d) actuation and reception strategies.

For brevity, Fig. 3 (a) reports a FEA frame, of the out-of-plane field output, regarding the reflected response of a 40 mm long artificial slot interacting with an orthogonal incident A_0 diagnostic wave; both the transmitted and reflected amplitudes are highlighted. Extending crack size from 0 mm up to 100 mm, a comparison between experimental and numerical outcomes is reported in Fig. 3 (b). Although the values between experimental and FE data differ, the trends are in good agreement: particularly a continuous non-monotonic function against the flaw size is highlighted, where maxima and minima coincide with the same flaw sizes.

Given the fact that nodal displacements and output voltage of a PZT are proportional each other, additional differences can be attributed to the discrepancies between the FE model and the real host structure, i.e. from damping, electro-mechanical coupling, residue A_0/S_0 mode excited by dual actuators in experiment, and crack shapes....

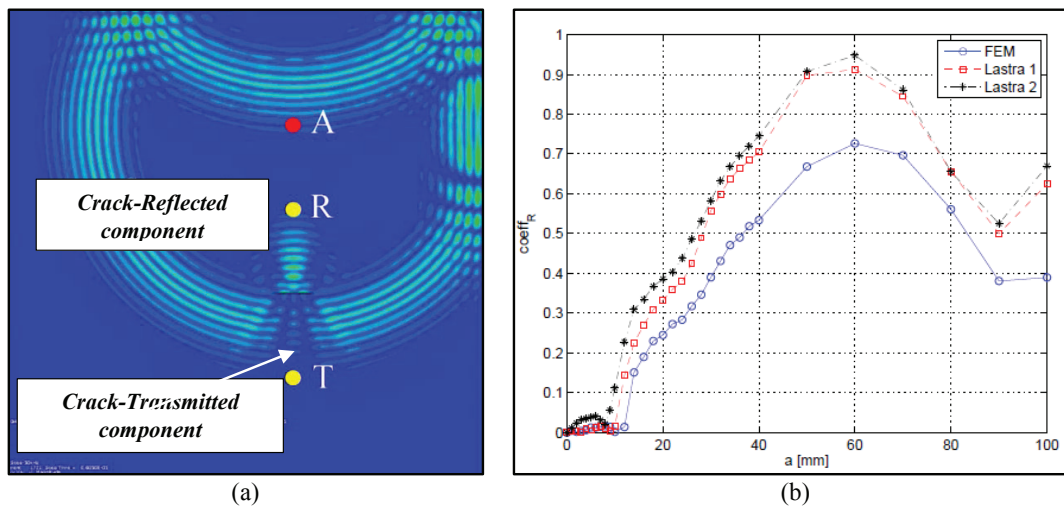


FIGURE 3. GWs response from artificial flaw: a) FEM snapshot, b) comparison between FE and experimental results.

MP-POD APPROACH

The Multi-Parameter formulation, formulated within the NDT field by Pavlovic [5] and successfully applied within a reliability nuclear framework [3], allows the description of the probability of detection of a flaw against different factors like flaw size (typical POD characteristic in Berens' model), orientation, position and attenuation. Experimental amplitude, describing the aleatory system response, is expressed against numerical simulations: since the theoretical model (simulation) gives the relationship between this response signal and the influencing parameters, it is now possible to calculate the POD curve as a function of all of the parameters at the same time. In particular, contrarily to the traditional model, in which the linearity between the signal and the influencing parameter is assumed just by observing the measured data set and/or from suitable transformation of the data, the relationship in the multi-parameter model comes from the simulation representing the understanding of the underlying physics of the process. Such an approach, developed to include and describe the influence of different deterministic parameters onto a POD curve, can also be used to linearize

highly non-linear responses, as those found here, and thus to get back the conventional Berens' statistical framework [1] using again a parametric physics based model.

In the present research, the considered deterministic factors are flaw size, orientation with respect to the PZT network and the selective Lamb mode, whereas the mounting process (glue thickness), piezo-electric properties, cabling, etc. are included within random factors. The former gives the slope and intercept of the regression between experimental and numerical amplitudes, the latter gives the overall variability around the mean value.

In an ideal case, if all the influencing parameters were included in the model, "Measured vs. Modelled response amplitudes" would lie on a 45 degrees inclined line. Dealing with the configuration of Fig 2 (d), where the pair of PZT actuators is fixed and the PE/PC response comes from all the PZT ring nearby the flawed area, amplitudes differ of a model factor to calibrate the modelled data to the experimental ones (Fig. 4 (a)). The estimate of the linear parameter is established by the well-known maximum likelihood estimation able of taking into account for censoring data. Its residuals, reported in the QQ-plot of Fig. 4 (b), clearly follow a Gaussian distribution.

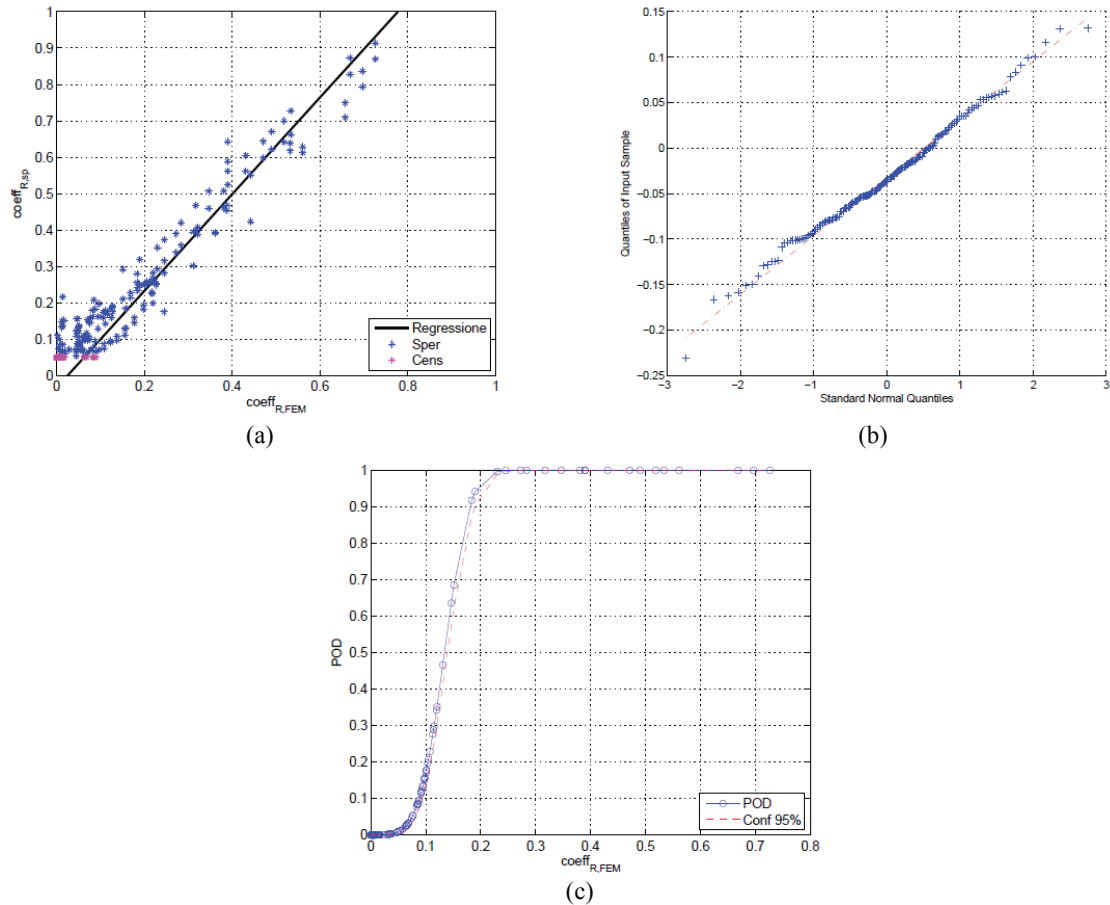


FIGURE 4. MP-POD formulation: a) Experimental amplitude vs numerical one diagram, b) Residuals QQ-plot, c) established Master POD.

Due to the linearity of responses, the homoscedasticity and normality of residuals, it is possible to formulate the master POD curve of Fig. 4(c) as a function of the numerical parameter. The latter, taking into account different combinations of parameters, allows splitting the master POD curve into the individual factors, as showed in Fig. 5 (a), (b) for A_0 and S_0 mode, respectively. The decision threshold was set equal to three times the noise maximum amplitude. As expected, the effect of an off-axis orientation with respect to flaw position reflects a right hand shift of the POD curve, thus leading to a higher $d_{90/95}$ value. Additionally, it is interesting to highlight that, above 45° , the $d_{90/95}$ parameter cannot be defined any longer. Regarding the A_0 mode, the classical monotonic S-Shape function is outlined, except for the 30° off-axis angle, where, at initial stages, the POD curve is negatively affected not only by ageing effects, but also by a particular crack size interval from 15 to 40 mm. Starting from 10 mm the POD values grow up to 30% and then immediately go down in a negative trend to 0%: just after 40 mm the classical trend is reestablished.

The aforementioned peculiar trend is less evident in the S_0 mode (much more smoothed), even if a peculiar trend is that after having reached a POD value of 100%, its POD starts to oscillate as illustrated in agreement with the physical behavior underlined in the FEA and experimental evidences.

From the point of view of the $d_{90/95}$ parameter, substantially there is no difference working with a particular fundamental mode regarding a through passing crack, although for higher off-axis angle the A_0 mode seems to be more sensitive. Again, this overall tendency is due to the same wavelength employing A_0 at a low frequency of 50 kHz and S_0 at a higher one of 280 kHz.

Finally, a POD value greater than 0% can be found for defect size starting from 10 mm, equal to half wavelength, both for the 50 kHz A_0 mode and 280 kHz S_0 one, which is in agreement with dispersion curves results and with the theoretical requirements of crack sizes larger than half-wavelength.

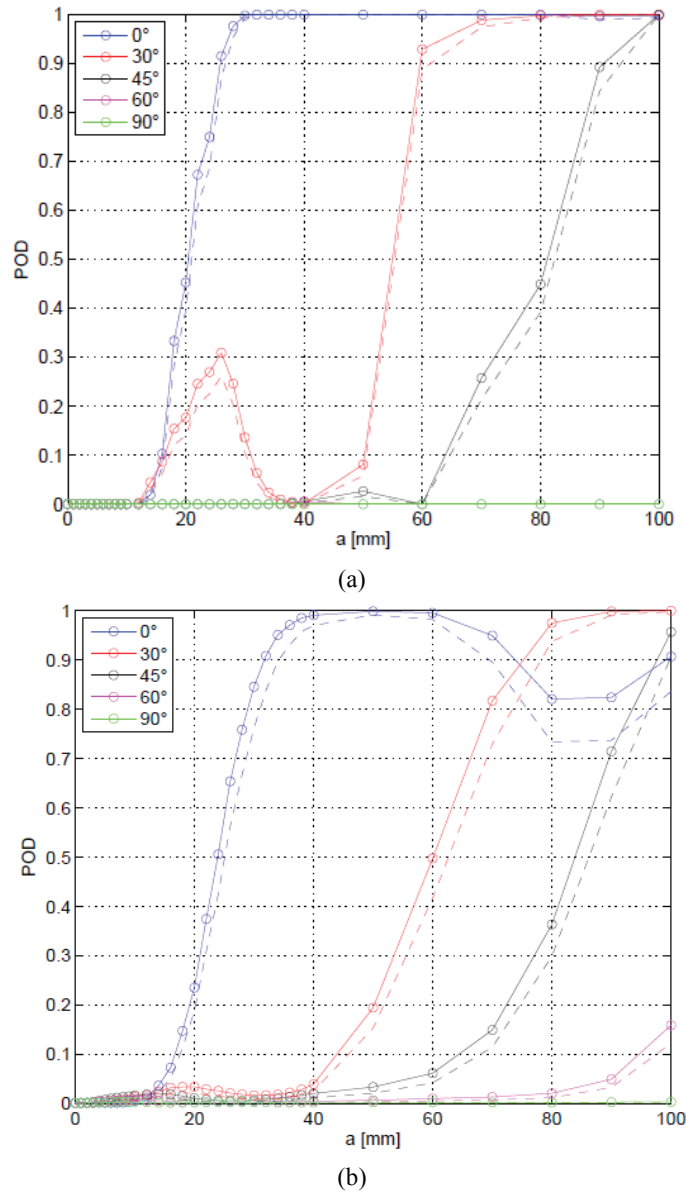


FIGURE 5. POD as a function of the defect flaw size with different sensors orientation: a) A_0 mode, b) S_0 mode.

CONCLUDING REMARKS

The authors investigated the feasibility of a Multi-Parameter approach, developed within the NDT field, combining experimental and numerical results for a SHM Lamb Wave based approach. Although in a preliminary study and using a simplified FE model, results seem encouraging. Particularly, its formulation allows the application of the conventional statistical framework used in NDT capability study, taking advantage of describing the influence of various factors with only one regressor, useful characteristic within a sensitivity study of GWs performance. As well as it is advantageous when highly nonlinear response concurs defining the overall response, event where a parametric model can be of difficult application and/or without any physical meaning. Once established the Master-POD of the system, it can be split in the

single component like crack size, orientation and Lamb Wave mode of interrogation. As a result, it is underlined that the POD curve can be a non-monotonic function of the crack size, but oscillations are present compatibly with the physical behavior both highlighted by numerical simulations and experimental data. Lastly, it is pointed out that a low frequency diagnostic wave, mainly concentrated in the A_0 mode, can carry the same amount of sensitivity regard a passing through crack, with respect to higher ones using S_0 mode. Such a conclusion is consistent with the fact that the wavelength of the two fundamental modes is approximated the same.

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