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Operational NDT Simulator, Towards Human Factors Integration in Simulated Probability Of Detection

Damien Rodat[1,a)], Frank Guibert[1,b)], Nicolas Dominguez[1,c)] and Pierre Calmon[2,d)]

[1]*Airbus Group Innovations, Toulouse, France*
[2]*CEA LIST, Saclay, France*

[a)]damien.rodat@airbus.com
[b)]frank.guibert@airbus.com
[c)]nicolas.dominguez@airbus.com
[d)]pierre.calmon@cea.fr

Abstract. In the aeronautic industry, the performance demonstration of Non-Destructive Testing (NDT) procedures relies on Probability Of Detection (POD) analyses. This statistical approach measures the ability of the procedure to detect a flaw with regard to one of its characteristic dimensions. The inspection chain is evaluated as a whole, including equipment configuration, probe efficiency but also operator manipulations. Traditionally, a POD study requires an expensive campaign during which several operators apply the procedure on a large set of representative samples. Recently, new perspectives for the POD estimation have been introduced using NDT simulation to generate data. However, these approaches do not offer straightforward solutions to take the operator into account. The simulation of human factors, including cognitive aspects, often raises questions. To address these difficulties, we propose a concept of operational NDT simulator [1]. This work presents the first steps in the implementation of such simulator for ultrasound phased array inspection of composite parts containing Flat Bottom Holes (FBHs). The final system will look like a classical ultrasound testing equipment with a single exception: the displayed signals will be synthesized. Our hardware (ultrasound acquisition card, 3D position tracker) and software (position analysis, inspection scenario, synchronization, simulations) environments are developed as a bench to test the meta-modeling techniques able to provide fast-simulated realistic ultrasound signals. The results presented here are obtained by on-the-fly merging of real and simulated signals. They confirm the feasibility of our approach: the replacement of real signals by purely simulated ones has been unnoticed by operators. We believe this simulator is a great prospect for POD evaluation including human factors, and may also find applications for training or procedure set-up.

INTRODUCTION

To ensure the safety of aircraft both in production and in service, Non-Destructive Testing (NDT) plays a central role whose reliability is crucial. The detection capability depends on a large panel of parameters: the structure, the defect, the procedure itself, the device and the operator. Statistical approaches are well suited to the random nature of the variations and this is the reason why a Probability Of Detection (POD) framework has been developed. For a given NDT procedure, a POD curve provides the probability (and the associated confidence domain) to detect the defect with regard to one of its characteristic dimensions. This information is used as input for the structure design and the maintenance plan definition in order to build damage tolerant structures.

The present paper focuses on one of the most unpredictable parameters that a POD must take into account: the human factors (inspected part accessibility, cognitive aspects, and also environmental factors influencing human behaviour). The first section is dedicated to the state of the art: to consider the operator in a POD study is still challenging when cost reductions are at stake. Therefore, a new concept of operational NDT simulator is proposed to combine the strengths of available approaches. In the last part, a proof of concept is investigated in the case of ultrasound inspection of Flat Bottom Holes (FBHs) in composite parts.

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POD ANALYSIS, STATE OF THE ART

The purpose of the following section is not to provide a comprehensive list of all POD techniques but rather to give the reader an introduction to the two main approaches.

Classical Approach (Experiment-based)

The classical approach to perform a POD analysis requires three steps:

1. *build 40 to 60 samples*. To decrease the costs, the manufactured parts are often smaller than the real ones.
2. *introduce defects into the samples*. This stage is probably the most critical one due to the difficulty to get realistic flaws with precise dimensions. By definition, a defect is an unexpected event occurring in the process; reproducing it on purpose might be difficult.
3. *inspect the samples*. Several operators evaluate the presence and the size of the defect.

The POD curve is finally computed based on the operators diagnoses making the full process very expensive and time-consuming. One analysis costs €200,000 on average! Nevertheless, this approach takes into account most of the human factors since the inspection is really performed by humans (note that organisational factors, part accessibility or inspection ergonomics might not be fully representative of real conditions).

Model-Assisted POD

The costs associated with a classic POD are explained by the large amount of experimental data which is required. In 2004, US researches of the Model Assisted POD (MAPOD) working group [2][3] introduced the idea of using models to build POD curves. With a simulation-based approach, most of the manufacturing costs — which represent 80 % of the total costs — vanish. Following this concept, European projects (SISTAE, PICASSO) have developed a computer-based process for POD studies [4]:

1. *define an inspection set-up*. All the input parameters required by the simulation process are provided, i.e. material properties, part geometry, flaw geometry, piezo-electric elements characteristics, probe position, etc.
2. *describe the variability of the influential parameters*. In reality, some of the input parameters are subject to significant variability. They must be identified and associated with a probability density function (pdf).
3. *propagate the uncertainty through the numerical model*. From the uncertainties in the input, the uncertainties in the output are deduced by taking into account the physical behaviour of the NDT technique.

Various case studies were investigated within Airbus Group on High Frequency Eddy currents Testing (HFET) for fatigue cracks detection in Titanium alloys [4], on ultrasound phased array testing of a rotating part [5] and of a complex 3D Titanium part [6]. Along with the improvements of the simulation software capabilities, the MAPOD technique can provide valuable results on more and more complex configurations. Interested readers can refer to [7] for a simulation-based POD best practices overview. These developments also brought the first users and customers feedbacks upon the technique [8]. Three recurrent questions arise: What if the input uncertainty are "wrong" or unknown? Can I trust the result from a simulation? How to consider human factors?

So, users point out the Achilles' heel of MAPOD: the choice of a pdf for each varying input parameters and more precisely the justification of the choices. Most of the time, the decisions are based on engineering judgements rather than on quantitative analyses (which could be expensive). The probability distributions of the input are thus questionable, especially when they depend on human factors. For instance, if the probe is held by an operator, then how to ensure that the tilt angle strictly sticks to a Gaussian distribution on average or how to evaluate the standard deviation.

OPERATIONAL NDT SIMULATOR

Figure 1 summarises the POD approaches with regard to the associated costs and ability to take human factors into account. State of the art techniques appear on the right: both of them suffer from a weakness either the costs or the human factors integration. From this statement, the idea of an operational NDT simulator able to combine the strengths of the existing techniques arises [1] (presented on the left-hand side of the Fig. 1).

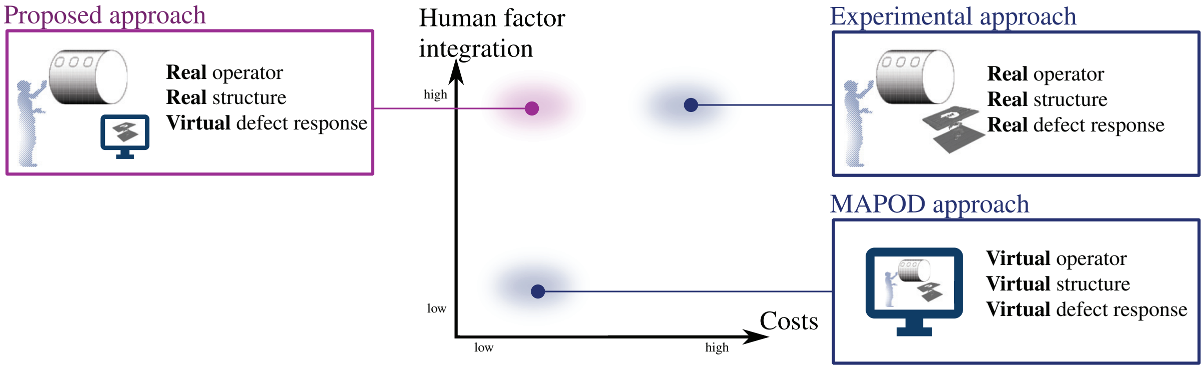

FIGURE 1. Perspective on the different approaches to conduct POD studies.

Concept

The best way to integrate the human factors probably remains to involve real operators as for classical POD. However, the major costs and difficulties associated with flawed parts manufacturing can be avoided by relying on simulations. Thus, the proposed system — called *operational NDT simulator* — looks like a classical NDT acquisition system that can be used by an operator. However, the signals which are displayed are synthetic signals.

As shown by the block diagram of Fig. 2, the operational NDT simulator is parametrized by a digital scenario which specifies the defects characteristics. Then, while the operator is scanning a representative mock-up of the part, his/her movements are captured. Based on both the real-time positions and the global parameters, an efficient synthesizer provides the corresponding NDT signals. As long as the model is fast and accurate enough, the resulting signals can be substituted to real ones on the NDT display. In the end, the operator will perform its diagnosis as usual (without noticing that the signals are virtual).

Since the operator environment is as close as possible to the real one, the operational NDT simulator immerses the user into the real operations: the human factors are taken into account *de facto*. Moreover, an infinity of different flaw scenarios can be investigated on a single mock-up if the corresponding models are available.

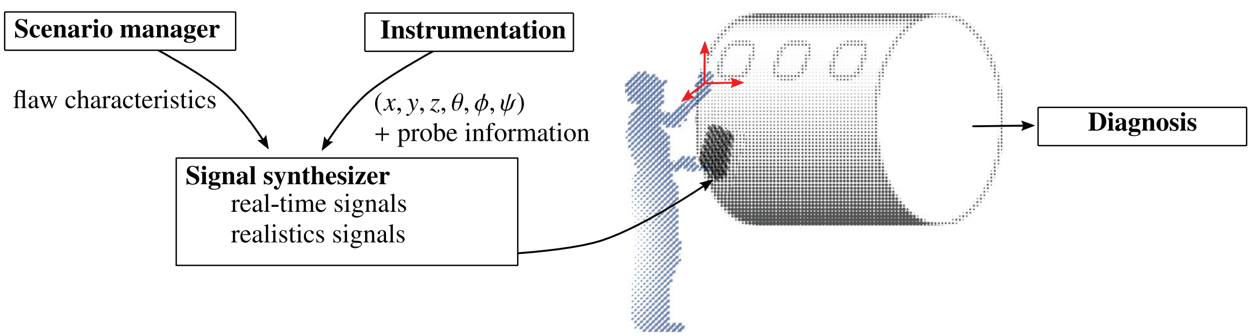

FIGURE 2. Block diagram of a typical operational NDT simulator.

Signal Synthesizer

The concept of operational NDT simulator is based on the possibility to produce realistic fast-simulated NDT signals: the operators should not perceive any differences between the simulation and a real NDT inspection. This statement challenges the available simulation techniques to decrease computation time without decreasing realism. Physical simulations are often based on a numerical solver which entails heavy computations. A finer solution hinders the time efficiency; a coarser solution hinders the realism.

An alternative solution is the meta-modelling framework. The system is seen as a black-box and a “general purpose mathematical approximations to input-output function" [9] is sought. A meta-model is always built upon known data (i.e. an a priori knowledge of the system). Different sources can be used such as complex and time-consuming simulations, real acquisitions or a combination of both. Then, the known signals can be played back (the sampling approach); or unknown signals can be inferred from the known ones (classical meta-modelling approach). The latter technique coupled with experimental data is a promising framework to tackle the challenge of high realism along with high computation speed.

A FIRST PROOF OF CONCEPT FOR ULTRASOUND NDT

In this work, an operational NDT simulator has been implemented in the case of *ultrasound NDT of carbon-fiber composite parts containing Flat Bottom Holes (FBHs)*. This test case offers a rather simple inspection set-up which is still of great interest for the industry.

Prototype Architecture

The operational NDT simulator is made of four main elements presented on Fig. 3. The probe position tracker provides the 3D position and orientation of the probe at 240 Hz. For each point, an ultrasound acquisition (32 elements, 4-element aperture, linear scanning with 29 shots) is triggered so that the A-scans can be tagged by the position at which they were measured [10]. Sent to a computer (typical configuration: PC 64 bits Intel® Core^{TM} i7-4710HQ CPU @ 2.50 GHz 2.50 GHz 8.0 Go RAM), the acquired A-scans are used to compute synthetic signals compatible with a given inspection scenario. The result are displayed under the usual form of A-scan, B-scan or C-scan.

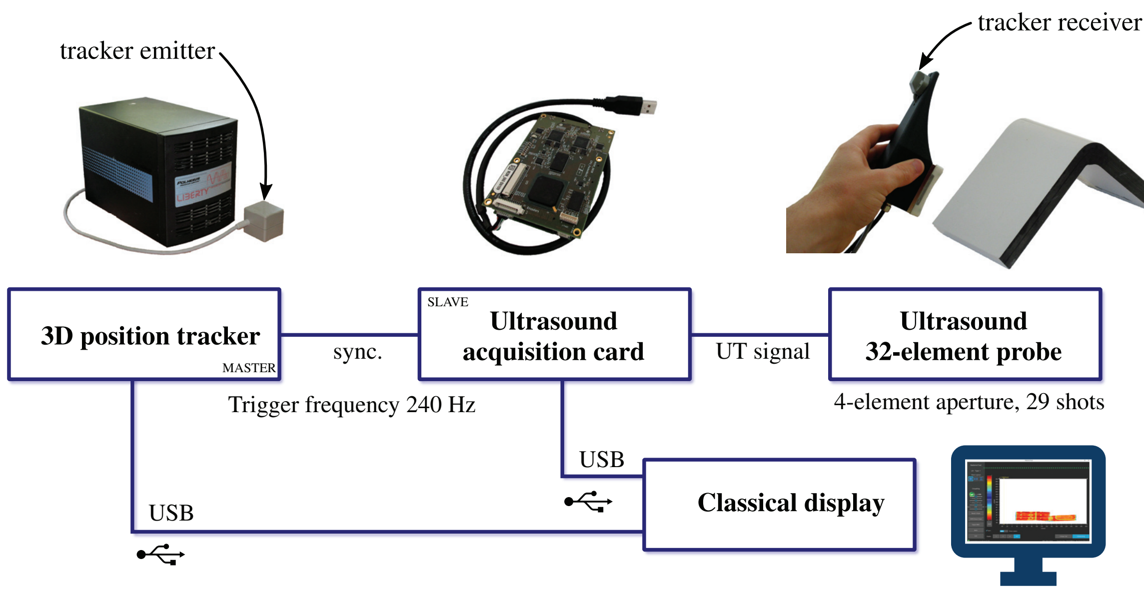

FIGURE 3. Architecture of the operational ultrasound NDT simulator prototype.

Signal Synthesizer: an Experiment-Based Model

For this prototype, 29 shots must be refreshed at 30 Hz (like the frame rate of movies). Thus, the synthesizer should be fast enough to generate one A-scan every millisecond. About the realism challenge, the composite material induces structural noise: the ultrasound signal changes smoothly from a defect-free position to another (a dynamic behaviour often referred to as the *living* aspect of the signal). Physics-based models require long computation time to render this feature; real experiments are thus more suited to capture it. Two choices were made: firstly, to synthesize the flaw signature with a meta-model based on experimental data and, secondly, to merge the model output with a real defect-free A-scan.

Flaw Signature Synthesis

In the chosen meta-modeling implementation, the input vector X consists of the FBH diameter Φ, the part thickness e and the coordinates of the flaw on the surface (x, y) (it is advocated that the FBH depth is constant with respect to the back of the part). The output vector Y corresponds to the flaw signature $s(t_0)$, ..., $s(t_N)$ (i.e. samples of a 4 μs-long waveform). The database on which the mathematical input/output relationship is computed is built upon experimental data only: an ultrasound acquisition is performed on a reference block containing 3 steps (7.23, 14.49 and 21.75 mm thicknesses) with 6 FBHs each (3, 4, 6, 7, 8, 9, 12 and 16 mm diameters). From the database, each defect is extracted and associated with the corresponding input vector. Once the input/output couples are constituted, the whole approach can be written as a mere regression problem. The final model must be able to output the ultrasound signal corresponding to any input vectors, as long as the components stay in the experimental variation range $e \in [7.23\ mm, 21.75\ mm]$, $\Phi \in [3\ mm, 16\ mm]$ and $(x, y) \in [0\ mm, 27\ mm]^2$. To solve this regression problem of limited size and subject to noise, the Gaussian process framework [11] was chosen.

Building a meta-model on experimental data offers a high level of flexibility and realism. For classical simulations, a large amount of parameters is required such as stiffness coefficients, fiber layout of the composite, attenuation law, geometry of the piezoelectric elements, etc. In practice, these details are not always available because of a lack of characterisation or due to confidential design elements. The proposed approach does not suffer from this limitation: the only requirement is to have an ultrasound scan of known defects. It should be noticed that the resulting model is highly specialised, i.e. is only valid for a given material and a given probe. Since the model construction takes nearly 10 minutes, generating a new model with a new probe is fast and straightforward.

Full Signal Synthesis

The presented prototype is used on a defect-free part so that an approach similar to augmented reality can be applied to the ultrasound signals. In fact, the flaw signature — output of the meta-model presented in the previous section — is merged with the real ultrasound acquisition made on the flawless part. As a result, the synthetic signal keeps a *living* aspect. For each scanned position, the following steps are performed (cf. Fig. 4):

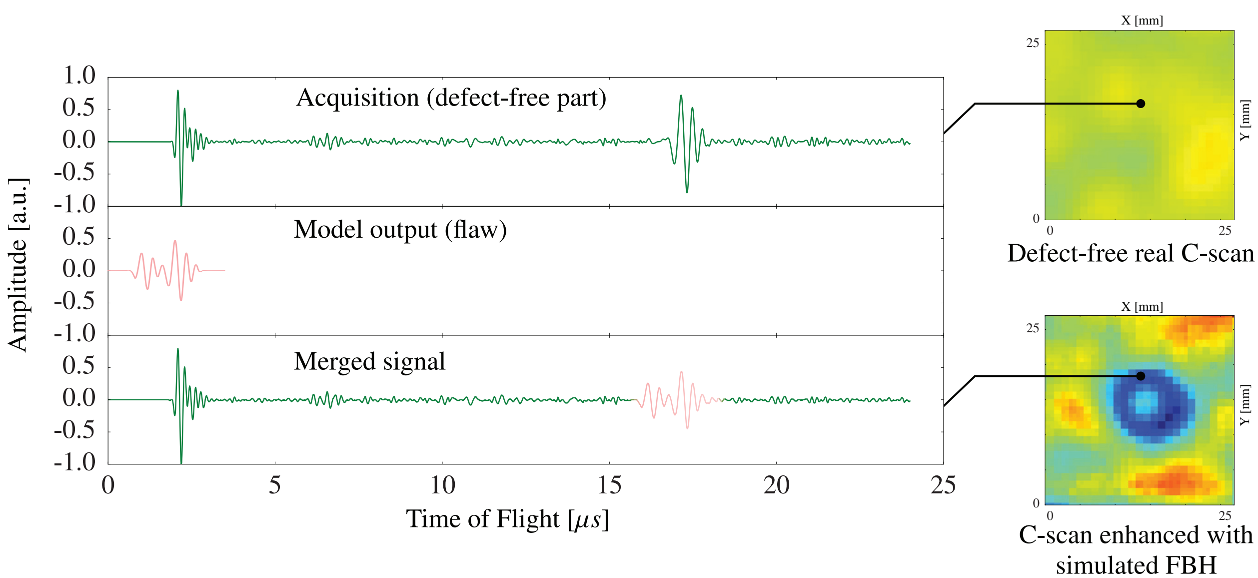

FIGURE 4. Merge of simulation and experimental signals.

- analyse the position with regard to the inspection scenario to state if a defect is required (if yes, retrieve its characteristics);
- detect the Back-Wall Echo (BWE) on the real A-scan and remove it;
- ask the meta-model for the corresponding flaw signature, adapt the scale to the real Front-Wall Echo and inject the simulation into the acquired signal;

The time-efficiency of the meta-model allows to process 2000 flaw signatures per second.

CONCLUSIONS

The most relevant and precise way to take human factors into account in POD studies is still to involve real operators. Based on this statement, the concept of operational NDT simulator is proposed: real operators facing synthetic signals into a real NDT inspection environment without the cost associated to the part manufacturing. Besides, a large panel of flaw types can be added into the structure according to an inspection scenario in a very flexible way.

A prototype was developed in the case of ultrasound inspection of composite parts containing Flat Bottom Holes (FBHs). The feasibility of the operational simulator is demonstrated especially in terms of *computation speed* and *signal realism* requirements. The challenge is addressed by an augmented reality approach applied to ultrasound signals along with experimental-based meta-models. The resulting signals are qualitatively very close to real ones, operators did not report any lack of realism. Besides, the implementation of the prototype is kept as modular as possible to be able to try new synthesis methods.

The operational NDT simulator could also be valuable for operator training: different inspection set-ups can be generated on a single representative mock-up. For now, only simple FBHs are available but the next steps will be to enlarge the parametrisation of the FBH and to simulate more complex use cases to enrich the possible inspection scenarios.

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