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## Data-driven modelling approaches combined to physical models for real-time realistic simulations

Damien Rodat<sup>1</sup>, Frank Guibert<sup>2</sup>, Nicolas Dominguez<sup>3</sup> and Pierre Calmon<sup>4</sup>

1 Airbus Group Innovations, France, [damien.rodats@airbus.com](mailto:damien.rodats@airbus.com)

2 Testia, France, [frank.guibert@testia.com](mailto:frank.guibert@testia.com)

3 Airbus Operations, France, [nicolas.dominguez@airbus.com](mailto:nicolas.dominguez@airbus.com)

4 CEA LIST, France, [pierre.calmon@cea.com](mailto:pierre.calmon@cea.com)

### Abstract

From manufacturing to in-service inspections, aircraft structures are under close monitoring through Non-Destructive Testing (NDT) techniques. A large number of these inspections relies on human operators, especially in the context of in-service airplane maintenance. The resulting signal fluctuations and diagnosis errors can be limited by careful operator training, and must be taken into account anyway when it comes to the qualification of NDT procedures or the development of diagnosis assistant algorithms. Managing human-related variability requires a large number of experiments involving different operators and flawed parts. For expensive aeronautical structures, the related costs are drastically increased. To tackle this challenge, the concept of operational NDT simulator was proposed. The simulator is equivalent to a classical NDT equipment but the displayed signals are generated using a mathematical model: expensive flawed parts are replaced by a representative mock-up and defects are numerically added where required. The underlying model must ensure a realism and a computation speed high enough to replace reality. Classical approaches to numerical simulations cannot meet both requirements; data-driven modelling techniques are thus investigated.

A proof of concept is proposed in the case of ultrasound inspections of composite structures. From the modelling perspective, the investigated strategy relies as much as possible on experimental data to ensure a high level of realism. Two different defect types are considered. A model of impact damage C-scans is built from a database of real impact inspections. The case of Flat Bottom Hole (FBH) defects is also studied with a meta-modelling approach applied on real data and enhanced by a physical knowledge. The resulting FBH model is able to efficiently replace real signals: certified NDT operators did not distinguish simulations from real signals. Thus, the operational NDT simulator can become a valuable tool to improve significantly any operations affected by human factors.



## **1. Introduction**

Most if not all NDT methods rely on a human operator. This crucial element of the detection chain induces variability and uncertainties. Real experiments are thus carried out to take these human and environmental factors into account. For instance, the design of new NDT procedures, the reliability assessment (Probability Of Detection studies) or the development of automated assistant algorithms need such real-condition tests. Having a real operator inspecting real defects requires manufacturing expensive parts. To decrease these costs, numerical simulations are often seen as a solution; however, the human behaviour is highly difficult to capture into a model.

In this paper, we introduce a new simulation approach called the operational NDT simulation. This concept combines numerical simulations with real-world set-up so that the behaviour of operators in real conditions can be directly studied. Section 2 develops the concept and the associated modelling challenges. Section 3 is dedicated to the hardware architecture required to build the bridge between the numerical simulations and the real world. Finally, section 4 presents the modelling strategy designed to tackle the operational simulation challenges in the ultrasound NDT context.

## **2. Operational NDT simulation**

The operational NDT simulation is designed to ease the access to NDT inspections in real conditions (1). Three use cases are targeted by this new concept. To turn this approach into a real tool, some scientific challenges are to be tackled.

### **2.1 The concept**

The operational simulation applied to NDT mostly consists in a real inspection scene. A realistic structure is available and the operator is equipped with a NDT device. However, the signals which are displayed on the device do not come from reality but from a signal synthesiser.

As shown on the block diagram of Figure 1, a numerical scenario manages the number, the type and the position of the flaws. During the inspection, the operator movements are captured and sent to the signal synthesiser. The synthesiser merges the information coming from the real world and the scenario requirements in order to provide the corresponding NDT signals. As long as this simulation process is fast and accurate enough, real signals can be replaced by the simulated ones on the NDT device.

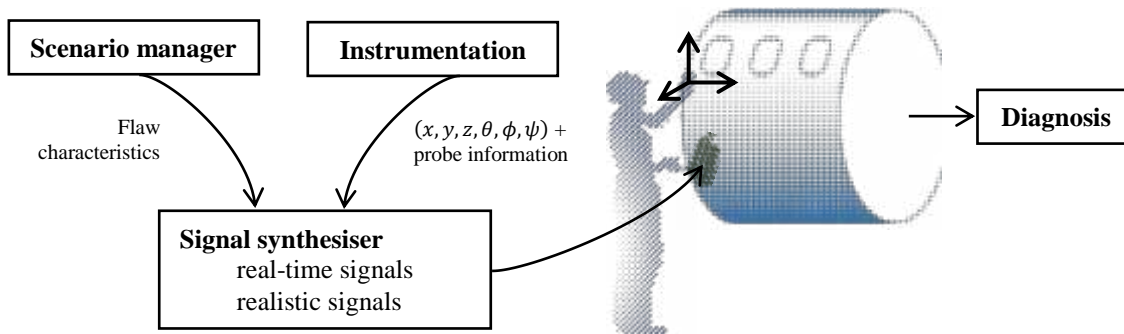


Figure 1 Block diagram of a typical NDT simulator.

On the operator side, everything seems to be real so the manipulations and interpretations will be as close as possible to the ones performed during a real inspection. The resulting diagnosis will be close to a real-world diagnosis and do not entail any complex manufacturing. With a single realistic mock-up, a wide range of different scenarios can be obtained without additional costs.

## 2.2 The use cases

The operational NDT simulation is explored in every condition where real-world manipulations are required on expensive structures:

- **Probability Of Detection (POD) studies.** In aeronautics, the POD studies are required to ensure the reliability of any NDT procedure. Typically, to perform a POD analysis, several samples are built. Defects of controlled size are introduced into the samples. Finally, several operators inspect the samples and the probability to detect the flaw with regard to its size is computed. Working with an operational simulator removes the large number of manufactured samples. Around 80 % of the POD costs can be saved.
- **Operator training.** During the training phase, operators need to be placed in real conditions. With real flawed samples, the inspection scenarios are limited to the available parts; with an operational simulator, many use cases are available.
- **New procedures and diagnosis assistant algorithms testing.** Designing a new procedure requires an access to the real structure so the operational NDT simulator can ease the process. Diagnosis assistant algorithms are also more and more used. In this case, the operational simulation can be used to collect data for machine learning purposes or to check the interactions between the operator and the algorithm.

### 2.3 The scientific challenges

The cornerstone of the operational simulation remains the synthesiser. The entire system relies on the possibility to replace real signals by simulated ones.

- **Instrumentation.** The synthesis requires an accurate characterisation of the real world parameters especially the probe position and orientation. These measurements must not hinder the operator movements. If a real probe is used in the simulator, the synchronisation of the position tracking and the NDT acquisition can enrich the real world information.
- **Computation speed.** To ensure a fluid scanning experience to the operator, the computations should be refreshed at least at 25 Hz.
- **Realism.** The simulation model must be able to deliver realistic NDT signals. The physical approximations applied in the model must not noticeably deteriorate the simulated signal.

### 3. Instrumentation integrated into a real NDT equipment

A first demonstrator of operational NDT simulator has been developed for ultrasound inspections (2). The hardware is based on the Smart NDT Tools<sup>®</sup> environment (3). Figure 2 shows the hardware architecture. The position tracking is based on an electromagnetic method which provides a wireless acquisition of the position and orientation of the probe. The accuracy nearby the tracker emitter and far from metallic structures (which distort the measurements) is below 0.1 mm and 0.1°. Each ultrasound acquisition is triggered by the 3D tracker so that A-scans are associated with the corresponding probe position and orientation. All the subsequent processing and display are inherited from the real NDT equipment. This integration with a commercial tool grants a usual and well-known interface to the operators.

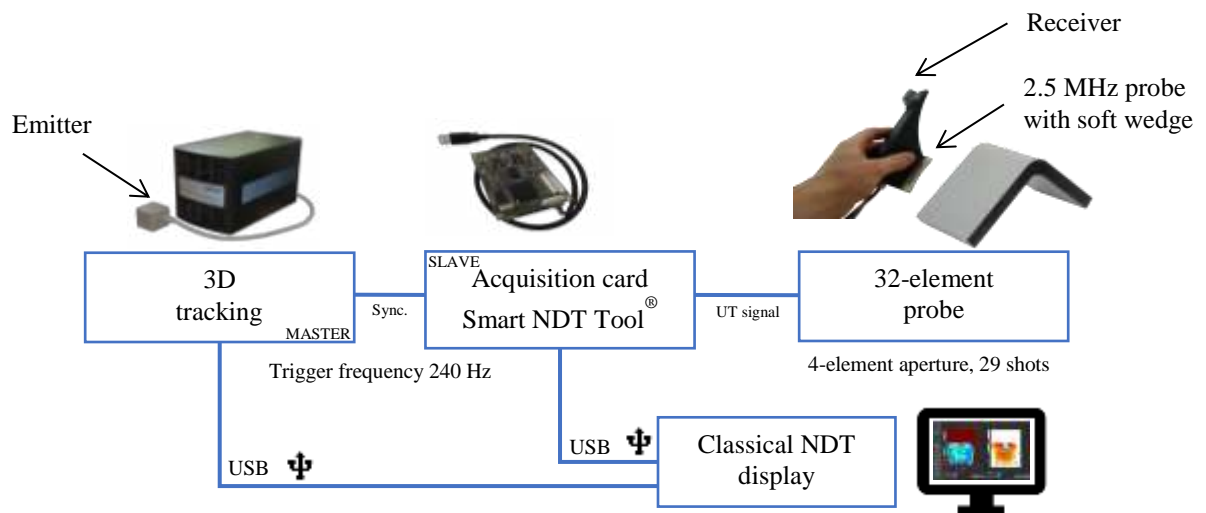


Figure 2 Architecture of the operational ultrasound NDT simulation prototype.

## **4. Data-driven modelling strategy**

The realism obtained with a numerical simulation is limited by two aspects. First, the computation complexity is often decreased by ignoring some of the underlying physical phenomenon. These approximations entail a lack of details which might be visually noticeable. Secondly, even if the computing power is high enough to run extensive physical models, a realistic simulation requires to know thoroughly the input parameters. The accurate measurement of material properties or the fine characterisation of the probe is very time-demanding and not always possible.

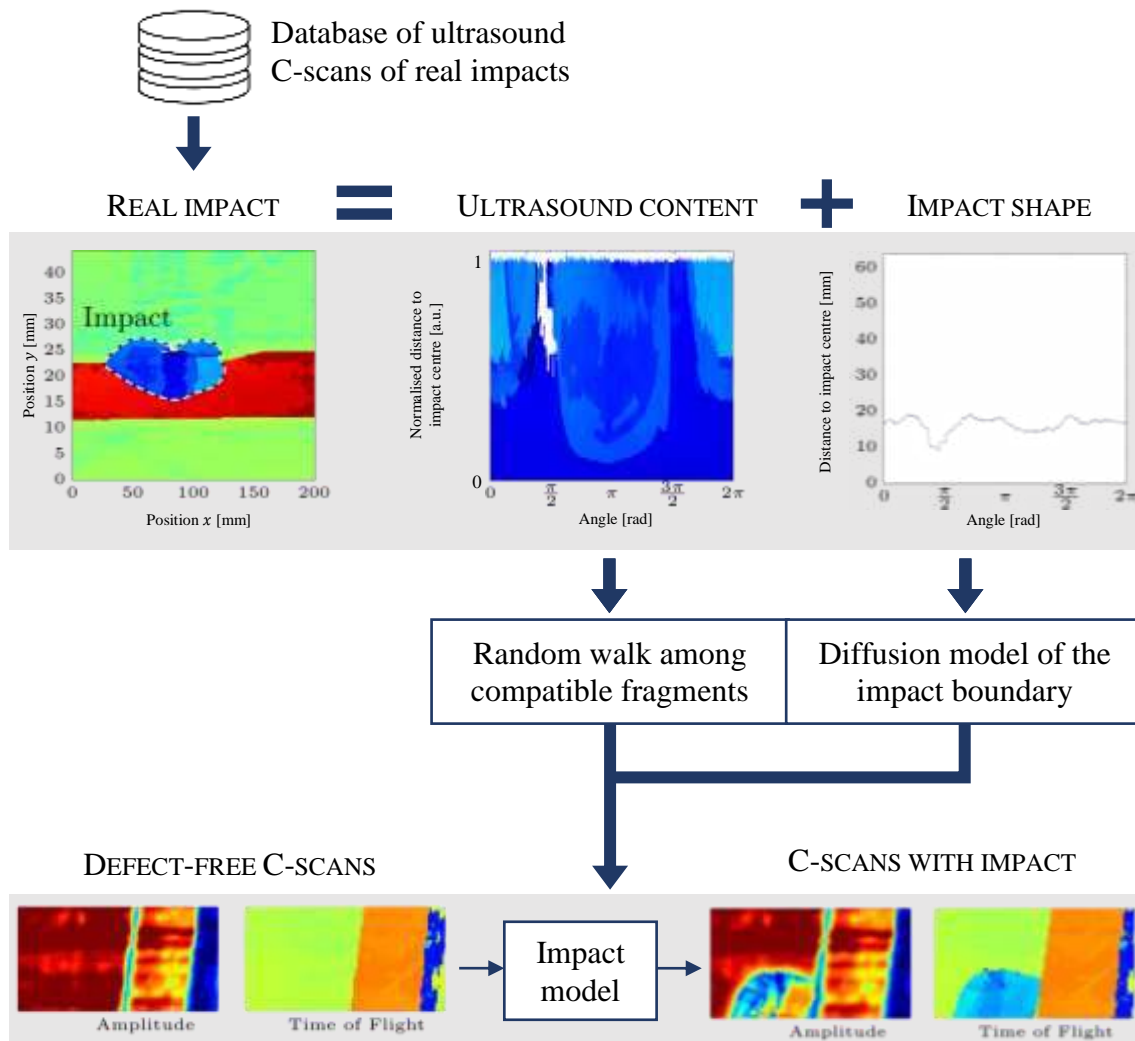
To tackle the realism challenge, we are investigating the use of real NDT signals. Why not learning the system behaviour from the measured signals when real experiments are available?

### **4.1 Simulation of impacts based on real experiment**

The case study presented in the following paragraphs deals with the simulation of impact damage C-scans (in amplitude and time of flight) on thin composite plates. As stated in (4), the mechanical simulation of an impact is still a challenge, namely due to the various involved scales (plate model, plies model or even fibre fracture model). Therefore, a fast ultrasound C-scan synthesis cannot be performed by a mechanical simulation of the impact characteristics followed by an ultrasound simulation; an experiment-based approach is investigated instead.

Within Airbus, a database of such C-scans is available. The exact conditions in which the impacts were made are not necessarily controlled; so, a parameterised physical model cannot be fitted to these data. Rather, the target is to reproduce the statistical behaviour of the impact properties extracted from the database. By doing so, the resulting model will be able to draw a random impact which looks like a real one without being one of the database.

The modelling approach is split in two phases as shown on Figure 3: the ultrasound content computation and the impact shape definition. This technique assumes that a known impact can be reasonably distorted to create various impact shapes. The ultrasound content of the impact refers to the time of flight and amplitude values which are measured above the damaged area. The impacts of the database are decomposed into several content fragments. The new ultrasound contents are built by combining available fragments, selected by a random walk among the “visually compatible” fragments. For now, the Manhattan distance is used to evaluate the visual compatibility; to get further, perceptual criteria should be investigated. The impact shape refers to the boundary between the damaged and undamaged area. Empirically, the shapes collected from the database seem to be coherent with a diffusion mechanism. Therefore, a diffusion equation with random initial conditions is implemented to model the behaviour of the impact boundary. The diffusion equation parameters are chosen so that the synthesised shapes display equivalent geometrical feature statistics than the ones observed in the database. To build the complete impact, the computed shape is filled with the ultrasound content.



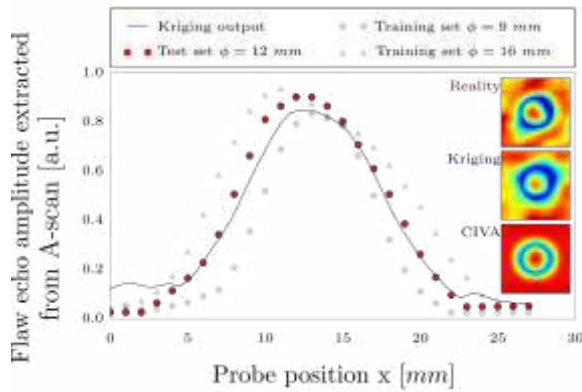
**Figure 3 Decomposition of the impact simulation into shape and content simulation.**

The first results of this simulation approach are displayed on the bottom part of Figure 3. Already used in the development phase of an impact sizing algorithm to generate corner cases, this impact model is still under development. The synthesis of the associated A-scan will be of primary interest to properly integrate the model into the operational NDT simulator.

#### 4.2 Modelling of Flat Bottom Hole (FBH) defect by kriging

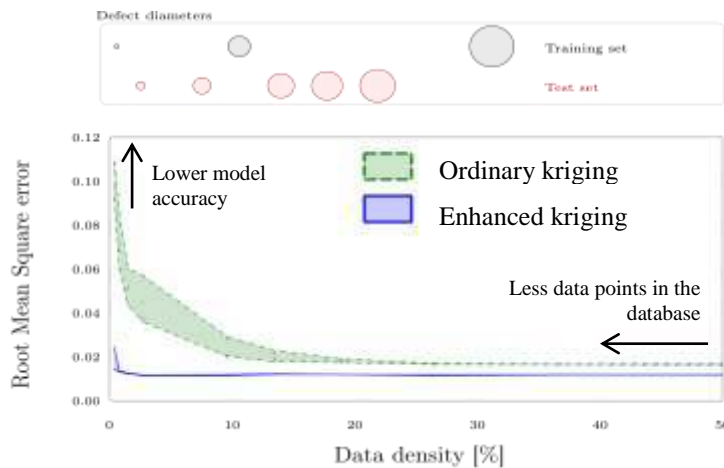
Another study to use real data has been conducted on a more classical model: the prediction of the ultrasound signature of a Flat Bottom Hole (FBH) defect in a composite part. In the aeronautic industry, FBHs are used as reference defects, this defect type is thus interesting to be integrated in the operational NDT simulator. The model is built with input parameters such as the flaw characteristics or the position of the probe. To ensure fast computations, the meta-modelling framework is investigated and more specifically the kriging approach (5). Kriging is a widespread technique which captures efficiently system behaviours even non-linear ones. The kriging approach is thus applied directly on real data: the resulting model outputs visually convincing defects, but to maintain a given

model accuracy a very large number of ultrasound scans are required. When different simulation parameters can be controlled, relying on real data requires to explore a large number of input parameter combinations, ending with many samples. For a limited range of FBH and a limited data noise, building the meta-model is possible as shown on Figure 4. The resulting meta-model was successfully integrated into the operational simulator. Coupled with the augmented signal strategy described above, this approach gives an interesting proof of concept.



**Figure 4 Meta-modelling approach applied on experimental signal.** The model is built on real measurements of two different diameters (training set) and tested on a third one (test set). The kriging result is given in solid line; the amplitude C-scan is also provided along with the real one and a reference simulation made with a commercial software CIVA®.

As displayed on this example, the data-based models are limited. They require large databases to learn accurately the system behaviour. The database construction can be expensive since real experiments – or accurate numerical simulations – are required. Another source of information is often available: the physical description of the system. The investigated solution is therefore to integrate this physical knowledge into the meta-modelling approaches. A method is proposed to introduce a physical model into the covariance function of the kriging technique (6). Implemented and tested on the FBH use case, the enhanced kriging shows a better generalisation property. Figure 5 displays the behaviour of the ordinary and enhanced kriging approach on simulated data of various density. Integrating physical knowledge helps finding a happy medium between the number of required data and the resulting accuracy.



**Figure 5 Integrating physical knowledge into the kriging approach decreases the number of required data points.** An ordinary kriging meta-model is built on three different FBH diameters with a very high spatial sampling. Then, the database density is progressively reduced by a random sampling. For instance, a density of 10 % means 1 point out 10 are kept. For each density value, 5 random samplings are performed to extract 5 sub-databases. Ordinary kriging is applied on the sub-databases and the physically enhanced kriging is applied on the worse and best sub-databases.



## 5. Conclusions

The operational NDT simulation is a solution to ease the access to real conditions by combining real-world inspections with numerical simulations. The manufacturing of expensive structure can thus be limited. This new approach challenges our modelling capabilities on three points: synchronisation of numerical model with the real world, computation speed and simulation realism. The synchronisation between the real and the simulated world relies on an accurate instrumentation implemented in our simulator prototype. Computation speed and realism are addressed by a modelling strategy based on real data: the system behaviour is learnt directly from real measurements of the output. This approach is applied on two different simulation use cases: the impacts on composite thin plates and the Flat Bottom Holes (FBHs) in composite blocks. Throughout these examples, the possibility to build a model from experimental data is shown as well as the resulting realism of the synthesised data. The last study on FBH illustrates a limitation of using only real measurements: the data requirement increases rapidly with the number of simulation parameters and may be too high to be fulfilled in practice. To overcome this difficulty, the data-driven model can be enhanced by a physical knowledge. A method based on kriging is thus proposed to combine real data and physical knowledge. The resulting meta-model relies on less experimental data to output realistic signals. An efficient modelling strategy can be reached by taking advantage of the realism brought by the real experiments and the generalisation properties brought by physics.

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