MODELING OF NDE RELIABILITY: DEVELOPMENT OF A 'POD-GENERATOR'

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Abstract: NDE in an in-service situation is used as a basis for integrity management as well as planning of future and maintenance actions. In such an environment it is of paramount importance that the performance level of the NDT method(s) used in terms of Probability Of Detection (POD) is known.

It is widely acknowledged that there is no such thing as '*THE POD'* of an NDE method or technique. This is because the POD does not only depend on the physics of the NDE method and the procedure used, but also on factors such as the degradation mechanism, the geometry of the component, accessibility, presence of coating or insulation, scope of sampling and personnel qualification and experience.

A number of industries in The Netherlands, among which chemical plant and pipeline owners as well as NDE service companies have initiated a Joint Industry Project to develop a model and corresponding software tool ('POD-generator') to assess the inspection effectiveness in a specific situation. TNO (institute of technology) is leading the project that has been launched in October 2003 and will take 3 years.

The focus in the project is on the inspection of pipelines and piping, newly developed and conventional NDE techniques as well as a number of specific degradation mechanisms. The paper will deal with the results of the project gained so far.

Introduction: With the introduction of Risk Based Inspection methodologies and similar prioritizing strategies for in-service asset management, the need to quantify the effectiveness of inspection procedures is greater than ever. The shift from intrusive inspection to non-intrusive inspection has compounded this need because it entails the loss of visual inspection as a tool. The performance of the non-destructive inspection is of critical importance to the management of the integrity because non-destructive inspection is increasingly the inspector's only 'sense'.

To devise the correct inspection specification, knowledge is required of the performance of non-destructive inspection and the factors that influence it. An inspection specification must be tailored to the specific application. For in-service inspection this means tailoring to the specific degradation mechanism and the way of managing the integrity. Inspection performance is a key factor in controlling the structural integrity of piping and pipelines.

At the end of 2003 a joined industry project has been initiated in The Netherlands with the objective to develop a comprehensive model for the assessment and optimization of a certain inspection approach. This model can be subdivided in three models, the inspection model, the degradation model and the integrity model. The main output of the degradation model is a surface containing modeled defects. The output of the degradation model serves as input of the inspection model. The output of the model is a probability of detection curve (POD-curve) for a specific situation. The main advantage of modeling POD-curves instead of measuring them is the reduction of time and cost. However this requires accurate and well-validated models.

The POD-curve(s) from the inspection model and the output of the degradation model serve as input for the integrity model. This model calculates the probability of failure.

Currently TNO is developing these three models. In this paper we will explain the contents and the mutual relation of these models in more detail and we show the progress that was made over the last nine months.

The 'POD-generator': The so-called POD-generator is a model, which allows the assessment and optimization of an inspection program for in-service assets. It is recognized that for an optimal operation of in-service assets, issues like degradation processes, inspection performance and structural integrity are all related and therefore should not be treated as separate issues. Within the 'POD-generator, there are three models, the degradation model, the inspection model and the integrity model. The degradation model predicts the initiation and growth of defects. With this project, the focus will be on uniform corrosion, localized corrosion and corrosion under insulation. The inspection model simulates the performance of an inspection method. It receives information from the degradation model in the form of defects. Information about the inspection performance is passed to the integrity model. This model predicts the probability of failure. These models are all interrelated, which we will illustrate on a simple example. Obviously, the inspection method depends on degradation mechanisms. The frequency and extent of an inspection depends on the consequences of a possible failure. During an inspection defects will be detected and action will be taken, if required, to repair these defects. This will improve the structural integrity. However for proper assessment of the integrity of an asset, knowledge about the performance of an inspection method is required for that given asset under inspection. Properties like the detection probability of (critical) defects quantify the performance of an inspection method. This property is commonly expressed in the form of a POD-curve (Probability Of Detection curve).

After each inspection, information is obtained about the growth and extent of different types of corrosion. This allows an update of the degradation model. The degradation model predicts the evolution in time of the defects. This information can be used to evaluate the probability of failure as function of time. It may for example turn out that the evolution of defects progresses faster than expected. Therefore it may affect the inspection interval, to maintain an acceptable level.

The objective is to develop a software package, which incorporates these three models. The user can use the software to evaluate different scenarios to evaluate or to optimize an inspection approach.

The degradation model: The degradation model describes the shape of a corroded surface in the form of a surface profile as function of lateral (xy) coordinates. Currently the main focus is on uniform and localized corrosion on the inside of pipelines and piping and on corrosion under insulation (CUI) and other degradation on the outside of pipelines and piping (e.g. supports). The method could in principle also be applied on other forms of corrosion as well, but this is beyond the scope of the current project.

In order to describe initiation of degradation and subsequent movement of a degradation front into a material, a descriptive modeling can be used to describe the evolution of the corrosion process as function of time. A Monte Carlo type calculation will be needed to come to a defect distribution, which can act as input for integrity and/or inspection models. The initiation stage is defined as follows: The probability that a surface cell A [m2] is initiated for the degradation mechanism in time step dt [s] equals Pi*dt [-]. The probability Pi [s^{-1}] depends on many parameters, like: temperature, medium, metal, surface condition, etc. But it depends also on the fact if a neighbouring surface cell is already initiated or not. Now, if the surface cell is initiated, the propagation starts. The propagation can be modeled like, (i) a growth rate da/dt [m/s] that occurs in every time-step after the initiation. The growth rate depends on parameters like: temperature, medium, metal, etc. But also the depth of the defect (a [m]), and possible the shape of the defect (da/dx [-]) can play a role. However it is also possible to model the propagation in a statistical way too (ii): the growth rate da/dt can be considered to consist of a probability Pp times a propagation step da, for each time-step.

Upon fine-tuning such a statistical model, a typical surface geometry of a corroded surface can be simulated, and the time-evolution can be calculated. This model is in principle able to describe all possible degradation mechanisms origination from the surface. With some modifications the model can be adjusted to describe internal defects as well. The main development during this project will be aimed on "calibrating" the input-parameters for good descriptive and predictive value of the model. Inspection results might be incorporated in a feedback loop, such that the corrosion model is becoming more and more realistic with time. The model is capable of producing different types of "corroded" surfaces, depending on the input parameters. Therefore, the challenge is to define the appropriate input parameters that are applicable to the corrosion under consideration. Corrosion may range from pitting to uniform corrosion. Examples of five typical corroded surfaces are given in figure 1. The figure illustrates that the general features of these types of corrosion can be reproduced by properly adjusting the model parameters.

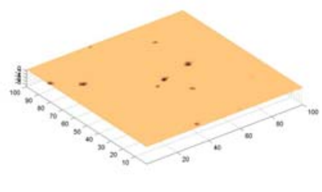
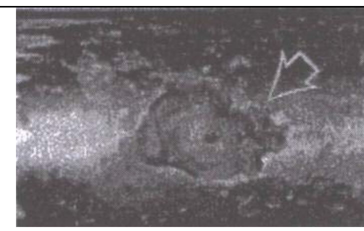
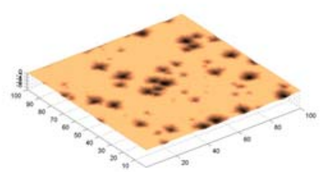
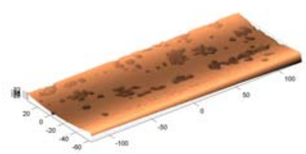
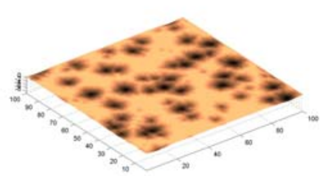
Statistical model	3D-scan of corroded surface	Photo of corroded surface
 *Type I: Isolated pitting corrosion*		
 *Type II: Overlapping pitting corrosion*		
 *Type III: Severe overlapping pitting corrosion*		

Figure 1: Examples of simulated corrosion types compared to real examples from the field**.**

The inspection model: The inspection model simulates an inspection technique. The focus in this project is on modeling ultrasonic and radiographic inspections. For modeling ultrasonic inspection techniques several algorithms are available based on finite difference scheme's [6,8,10] and the Kirchhoff integral [11]. Modeling of radiographic inspection techniques is done using a Ray-tracing algorithm [12].

The output of the inspection model is either a inspection result for specific situation or a POD-curve based on a sufficiently large number of simulations.

Figure 2 summarizes the modeling approach; it basically consists of two steps:

- Numerical simulation of inspection;
- Generation of the inspection result.

In the first step the physical experiment is being modeled. The output of this simulation could be a measured signal at a certain location by a specific sensor. This result itself is not yet an inspection result it requires a certain processing/interpretation. To obtain an inspection result, the inspection procedure should be applied and combined with certain detection criteria. After applying this procedure, an inspection result is obtained. This can either be the detection of a defect and/or characterization of a defect in terms of size, location and type of defect.

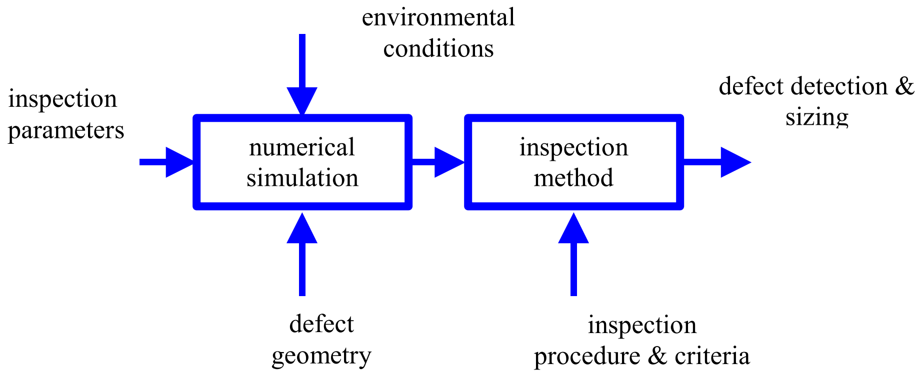


Figure 2: Schematic set-up of the inspection-modeling environment.

Obviously, the numerical simulation of a physical measurement requires several input parameters, which can be categorized in three main groups:

- Inspection parameters;
- Defect parameters;
  - Material properties;
  - Object properties;
  - Defect geometry;
- Environmental conditions.

The inspection parameters refer to typical system settings of an inspection technique. They can be subdivided in the equipment parameters, the sensor parameter and the positioning/scanning parameters. Statistical variation can be introduced in these parameters to simulate realistic variations as they occur in the field. For example, in case of ultrasonic inspections, variations in coupling and transducer positioning are taken into account.

Proper description of the defect geometry and geometrical features of the inspection location is very important to obtain accurate results. Within this project mainly two types of detects are considered:

- General corrosion, which is an overall reduction of the wall thickness
- Local corrosion, which has a shape of small pits in the material.

The defect description is obtained from the degradation model. With respect to geometrical properties of the inspection location, the geometry will be limited to fairly simple geometries as can be expected in piping and pipe-lines.

Parameters that characterize a defect are:

- Size;
- Orientation;
- Shape (surface roughness)
- Material inside the defect (fluid or air).

Environmental parameters are these parameters that affect the measurement. In order to obtain realistic results, these parameters should also be included in the numerical modeling of the inspection technique

The inspection method simulator also requires input. The main input parameters are:

- Output of the simulation module;
- Inspection procedure and criteria.

The output of a numerical simulation is not yet the result of an inspection. The output of the simulation is a simulated measurement, i.e., a measured response at one or more detectors. This simulated response is the input of a module that generates the actual inspection result. The inspection result can be divided in two categories:

- Detection of a defect (screening techniques);
- Characterization (sizing) of a defect.

In order to arrive at an inspection output, the simulated measurement signal should be treated according to the procedures related to a specific inspection method. The inspection procedure also provides defect detection criteria. This will produce the final inspection result.

Comparison of the inspection result with the known properties of the defect, allows us to determine the inspection performance. The inspection performance can be expressed in terms of a probability of detection curve (POD-curve). To types of POD-curves are distinguished:

- The inspection technique related POD-curve;
- The inspection procedure related POD-curve.

The inspection <u>techniques</u> related curve shows the fundamental capabilities of an inspection technique. Due to noise in the system and other system related properties an inspection system can only detect a certain range of defects. Therefore the POD-curve for the inspection technique is not equal to unity for all defect sizes.

The POD curve for the inspection <u>procedure</u> shows the probability of detection when using certain inspection techniques combined with the inspection procedure. In general the detection probability for the inspection procedure will be lower than for the inspection technique, since the POD-curve for the inspection assumes an ideal defect illumination. Also all kind of human factors are incorporated in the inspection procedure related POD-curve.

From literature two different types of statistical models for calculating POD-curves are known, one based on binary input, e.g., defect detected or not, and the other one uses a continues variable, e.g., defect height. The binary model is generally referred to as the generalized linear model (GLM) [1,5,9].

The continuous model is generally referred to as the â versus a model [2,5,9]. A more detailed discussion about these models is beyond the scope of this paper.

Example: We illustrate the inspection model using a simple example of pulse-echo ultrasound measurements. This example is intended to illustrate the concept of the 'POD-generator'. Pulse-echo measurements are used to find and size corrosion defects in a pipe wall. The simulation software is based on a semi-analytical modeling approach [11]. With this simulation software many effects like surface roughness and transducer coupling can be simulated.

In this example a 4 MHz, 0.5-inch ultrasonic transducer is used. In this example the width and depth of defects is varied. The depth varies from 0 to 8 mm and the width varies between 0 to 160 mm. Since the exact position of the defect is unknown, the transducer is placed at random locations. An amplitude threshold is applied for signal validation; if the amplitude is below that threshold the transducer is moved to another location. If a proper signal is measured, the wall thickness is determined from the measurement. A defect is found if the nominal wall thickness is reduced by 10%. By this means the continuous wall thickness measurement is translated to a binary defect detection criterion.

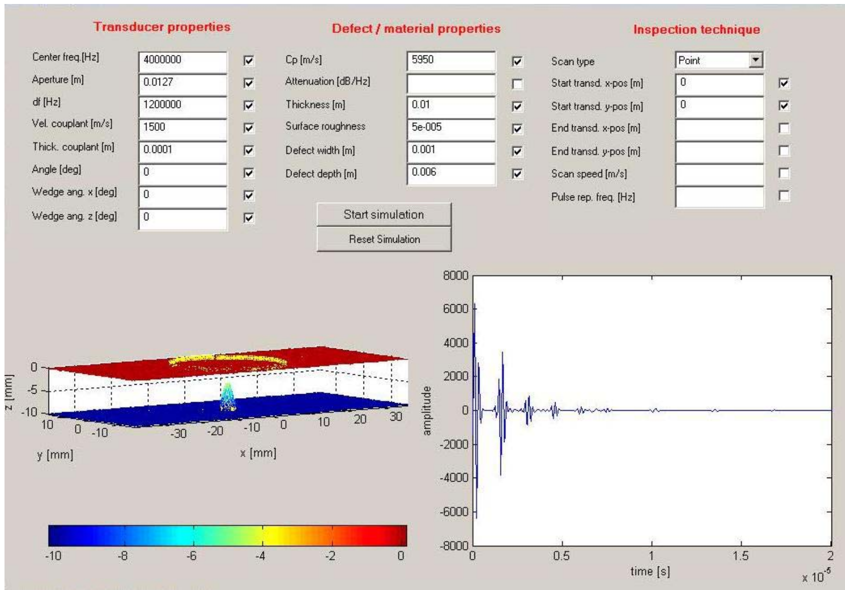


Figure 3: Example of ultrasonic pulse-echo simulation software.

The POD-curve is calculated based on the detection using the GLM-model. The POD-curve was calculated for a fixed defect width and a varying defect depth. POD-curves as function of defect depth and width are shown in Figure 4. The detection probability of narrow defects turns out to be very low, this is not a principle limitation of the inspection technique itself but simply caused by the measurement procedure. Once the defect becomes wider, defects are more easily detected. This nicely illustrates the difference between the inspection technique related POD-curve and the inspection procedure related POD-curve.

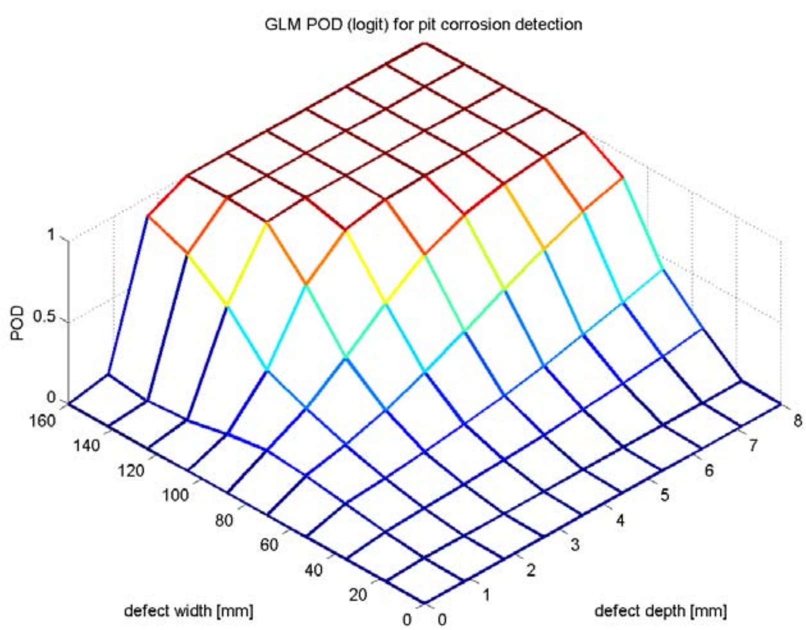


Figure 4: POD-surface as function of defect depth and defect width.

The integrity model: The Integrity model in this project is used for the calculation of the probability of Failure (POF). The main function is to show the influence of the inspection procedure or inspection effectiveness on the integrity of the appliance or part concerned. In first instance the model will be focussed on pipelines and piping. In this project the integrity model will be limited to these two types of flaws: sharp defects (fracture mechanics (FM)) and wall thinning by corrosion approach local corrosion (LC), which includes general corrosion. In terms of fracture mechanics by definition all types of flaws will be regarded as sharp defects. Separate solutions are available for surface breaking and embedded defects.

The formulas to be used for the FM approach will be based on BS7910. This British standard is commonly used in Europe and a related European code is in preparation. Further detailed analyses, for instance effect of weld strength mismatch, influence of strain hardening and yield to stress ratio, effect of weld geometrical mismatch, etc. will not be used in the integrity model in this stage. It is expected that such detailed analyses will have a minor effect on the resulting conclusion about the inspection effectiveness.

For corrosion type of defects (wall thinning) several formulas are developed (BS 7910 Annex G, DNV-99, Shell-92 [3], Pandey[4]). The DNV-99 and Shell-92 model are based on the tensile strength, as Pandey is based on the yield strength.

For the calculation of the reliability as a result of an inspection procedure a Monte Carlo Simulation is used. The program starts with drawing a random defect size from the defect distribution. The defect distribution is derived from the degradation model. For this defect a random number will be drawn to determine whether it is detected during inspection. The POD-curve from the inspection model is used here to determine the probability that the defect is found. If the defect is indeed found during inspection, the defect size is determined. Again, the sizing accuracy is also determined in the inspection model. If the measured defect size is too large, that it exceeds the repair criterion, it will be repaired and therefore poses no longer a threat to the integrity of the structure. If the defect is not repaired, the growth and the actual defect size are used to determine whether that defect leads to a failure before the next inspection. This procedure is repeated a larger number of times such that an accurate estimate can be made of the probability of failure.

Interesting scenario studies can be done within this simulation environment, for example different inspection techniques; inspection procedure (coverage of surface area), inspection intervals repair criteria etc. can be compared.

Heerings et al.[7] show the effect of the inspection technique, coverage and sizing accuracy on the probability of failure. With this knowledge the inspection cost and economical risk due to failure can be balanced.

Conclusions and future work: To assess the inspection effectiveness of a certain inspection procedure in a specific situation, a model describing the relationship between the many controlling factors is being developed. The key components are the degradation model, the inspection model and the integrity model.

The model under development will be a software tool, which can be used by the inspection firms and the end-users to design and optimize an inspection program both technically and economically.

The degradation model contains a generic approach to model various degradation processes. Currently the main focus of the degradation model is on uniform corrosion, localized corrosion and corrosion under insulation. It has been shown that with the proper parameter setting in this model, various types of corrosion can be accurately modeled.

A general concept of modeling inspection techniques has been introduced. The inspection model contains two blocks, one that simulates the physical inspection process and the other creates the inspection result taking into account a certain inspection procedure. The current focus is at ultrasonic and radiographic inspection techniques. The future activities mainly aim at quantifying all parameters that affect the measurements. Already a lot of literature is available for this purpose. The disturbing parameters will be included in the modeling, such that realistic POD-

curves are obtained. The project includes NDE experiments and comparisons with existing NDE field data to evaluate the model.
The integrity model requires input from the degradation and inspection model. This input is used to compute the probability of failure of a piece of equipment. With the integrity model interesting inspection scenarios can be evaluated in terms of inspection cost and failure risk.

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