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EARLY WORK ON THE USE OF MODELS IN THE DETERMINATION OF POD/INSPECTION RELIABILITY IN THE US AND UK

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ABSTRACT. Early demonstrations of the use of models in the U.S. and U.K. to assist in the determination of NDE reliability and probability of detection (POD), as dictated by the advent of damage tolerant design, will be reviewed. A major motivation in the U.S. was the adoption of POD as the primary metric for effectiveness of an inspection and the empirical observation that field and depot inspections were not adequate to support the desired structural integrity. In parallel, a series of round robin trials in Europe raised issues with the effectiveness of nuclear power plant inspections, and the resulting concerns became an important part of the “Public Inquiry” in the UK regarding the construction of the Sizewell B power plant. In each country, physics-based models of the inspection process became an important part of the response. This paper describes these early developments in the use of models to assess inspection reliability, contrasts the philosophies and approaches taken, and notes how these provide the origins of NDE simulation activities today.

Keywords: Inspection Reliability, POD, Worst Case Flaw, Structural Integrity

PACS: 43.35.Zc

INTRODUCTION

The need to assess inspection reliability and its statistical metric, POD, was enabled by the development of fracture mechanics and other models of material degradation and failure. These models formed the basis for replacing traditional structural integrity strategies such as safe life design by damage tolerant design in which, among other things, it was recognized that structures might initially contain flaws and physical understanding (e.g. fracture mechanics in the case of metal fatigue) was used to estimate the time that it would take for these to grow to failure in a controlled fashion. The reliability of NDE, i.e. the size of flaws that could be confidently detected, then became the basis for the design and life management for many structures; such are found in the nuclear, aerospace and transportation industries where failure can have catastrophic consequences in terms of loss of lives, money or readiness. An excellent discussion of the fundamentals, with emphasis on the aerospace industry, is provided by Grandt [1].

MOTIVATION FOR THE USE OF MODELS

In the United States, the Air Force played a major role in implementing damage tolerant design, driven by such events as the premature failure of an F-111 aircraft at a small fraction of the life expected on the basis of its safe life design (fatigue crack
initiation criterion for nominally defect free initial material) due to a large manufacturing defect that was not detected [1]. Implementation was done within a partially probabilistic framework [1,2] in which deterministic failure predictions were combined with an inspection limit inferred from Probability of Detection (POD) curves, often as the flaw size for which the POD is 90% with 95% confidence (90/95 criterion). The determination of POD became an important component of engine and airframe structural integrity programs and experimental procedures were developed for determining POD [3, 4].

With POD established as an important ingredient in structural integrity programs, an evaluation of inspection capability, as realized in the depot and field by Air Force Logistic Command personnel was undertaken, the so called “Have Cracks, Will Travel Program” [5]. Figure 1 shows the results of the analysis of data from 15 bases for ultrasonic and eddy current inspections of a sample from a C-130 wing box. It was very disconcerting that the 90/95 criterion was not reached for crack sizes up to ¾ of an inch.

In the United Kingdom, an intensive effort to use models to assess inspection reliability was motivated by the desire to build a major nuclear power plant (Sizewell “B”) and the associated safety concerns. A Public Inquiry was held to determine whether the project should be allowed to proceed (1982-1985). This was a formal opportunity to debate in public Britain’s future policy on nuclear energy and Sir Walter Marshall led a senior study group. This group was satisfied with the PWR vessel integrity. However, substantial recommendations were made for improvements in ultrasonic NDE beyond those required by the ASME boiler and pressure vessel code, a conclusion that was strongly influenced by the Plate Inspection Steering Committee (PISC) round robin studies in which some large flaws were missed by techniques following that code. The use of models was an important ingredient of establishing the reliability of proposed NDE procedures and thus provided a key input to the Public Inquiry, as will be discussed subsequently [6].

EARLY MODELING EFFORTS TO ASSESS INSPECTION RELIABILITY IN THE US

The concerns raised by the “Have Cracks, Will Travel” program led to a new charge to the research community [7]. It was noted that for structural evaluation, the ultimate sensitivity of an inspection technique was not of major importance. Rather, it was pointed out that the critical parameter is the flaw size that can be reliably detected every time. It was recommended that traditional research approaches should be modified

FIGURE 1. Result from AFLC Depot/Field NDI Capability Evaluation Program.
towards this end. The context for this recommendation included a large research program that had been created by the Advanced Research Project Agency and Air Force Materials Laboratory in 1974 to create a science basis for inspection as demanded by the more quantitative requirements of damage tolerant design. That program led to the organization of the now international Review of Progress in Quantitative Nondestructive Evaluation.

Figure 2 shows the conceptual outline of the envisioned response, outlining first steps to an engineering response [8]. In that paper, detection modeling was identified as an important research topic. Some of the elements that existed at that time (1983) and that were envisioned to be still needed are identified in Fig. 3. The science base until that time had focused on understanding the scattering of elastic waves from a flaw in an unbounded medium. Some of the additional factors that needed to be considered are illustrated in Fig. 4 [9].

A vigorous research and development effort followed, including work by Tittman, Ahlberg, Fertig, Richardson and Elsley at the Rockwell Science Center and Thompson and Gray at the Center for NDE at Iowa State University. A number of research papers in Volumes 3 and 4 of the Review of Progress in QNDE describe those results. Figure 5, from the former group, illustrates an assessment of the ability of detection filters to improve POD [10]. Figure 6, from the latter group, illustrate an assessment of the latter group on the effect of scanning on POD [9]. This work was conducted in the context of the problem of inspection the bore of a turbine disk using a 45° refracted shear wave. The

![Figure 2](image1.png)

**FIGURE 2.** Generic NDE building blocks: First steps towards an engineering approach.

![Figure 3](image2.png)

**FIGURE 3.** Detection modeling identified as an important research topic.
FIGURE 4. Illustration of phenomena that need to be considered in developing a detection model.

FIGURE 5. Effects of filtering on POD.

Inspection
45° refracted shear
Threshold
50% of .16 cm crack

Variabilities
Tilt: ±10%
Skew: ±10%

Δ(rθ) = .254 cm
Δ(z) = .254 cm
Δ(rθ) = .127 cm
Δ(z) = .508 cm

FIGURE 6. Effects of scan increments on POD of Detection of Cracks through bore of aircraft engine rotor.
crack was assumed to have a distribution of orientations, centered about cracks oriented in the radial direction and uniformly distributed with $\pm 10^\circ$ tilt and skew. The focusing of the beam by the curved surface required different scan increments in axial and circumferential directions to maximize POD.

The growing acceptance of the importance of modeling in assessing NDE reliability was recognized by inclusion in Volume 17 of the Metals Handbook of a review of this approach that included a discussion of eddy current and x-ray approaches as well as ultrasonic approaches [11].

**EARLY MODELING EFFORTS TO ASSESS INSPECTION RELIABILITY IN THE UK**

Prong 1 of the NDE response to the Public Inquiry was the Defect Detection Trials. A set of test blocks were fabricated to experimentally demonstrate the ability of ultrasonic procedures to detect, locate and size a wide variety of defects in vessel seam welds and under cladding. These were invaluable in establishing confidence in the practical application of ultrasonic procedures but fell short of a complete demonstration of reliability because the limited number of defects was too small to support statistical claims of very high reliability.

This led to Prong 2 of the NDE response, the development, at the Central Electricity Generating Board, of quantitative models to interpolate between and extrapolate beyond the responses observed for the particular defects examined experimentally. To this end, models for the tip diffracted signals were developed using the Geometrical Theory of Diffraction and for specular reflections using the Elastodynamic Kirchhoff approximation [6, 12]. Figure 7 illustrates these with a sketch of the physical phenomena leading to the diffracted signals (left) and a comparison of model predictions and experiment of the Elastodynamic Kirchhoff prediction (right). The latter was one component of an extensive experimental validation program.

![Geometrical Theory of Diffraction and Elastodynamic Kirchhoff](image)

**FIGURE 7.** Component of the modeling efforts in response to the Public Inquiry.
Given these validated models, assessment of reliability was based on the prediction of the detectability of a postulated “worst case” flaw. In contrast to the probabilistic, POD based approach described above, this required a deterministic calculation for plausible extreme cases judged to be the most difficult to detect. This procedure needed a good defect specification of what flaws were plausible (consistent with the design and operating conditions of the PWR) and had the possibility of being too pessimistic since occasionally missing highly unlikely defects might not compromise safety.

However, these were believed to require less difficult judgments than the comparable ones required in a POD-based approach. In that case, one would have to judge how high the POD needs to be and the nature of the statistical distribution of defect properties.

The least detectable plausible defect of structural concern for the ultrasonic inspection of the PWR RPV seam weld was judged to be a 20 mm diameter, circular crack located 70 mm below the vessel surface and tilted 8° to 10° from a plane perpendicular to the surface. It was postulated that the roughness was such that the diffracted signals (the basis for detection) were attenuated but the diffuse scattering was weak. The modeling approach was to calculate the signal as a function of probe position for a smooth crack, develop a detectability index in terms of number of hits and peak amplitude, and derate the results to take into account experimentally determined effects of crack roughness and cladding. Figure 8 provides an example of the first step of such a calculation.

The above work was based on applications of the elastodynamic scattering theory that took into account the existence of shear as well as longitudinal waves. As noted above, a deterministic approach was taken to establishing the reliability of the proposed worst case flaw for the proposed inspection for Sizewell “B”. However, it will also be recalled that the important motivation for the concerns that led to the Public Inquiry was the inspection problems that were observed in the PISC round robin trials. Haines, working in the Berkshire facility of CEGB, conducted a statistical analysis of that data [13]. This was based on the scalar Kirchhoff approximation (not taking shear waves into account) and included empirically determined beam patterns to model the intrinsic “capability” of various inspection schemes for the PWR RPV seam weld. The PISC-I data was used to estimate team-to-team “variability” in practice. By combining this “capability” and “variability” data within a statistical framework, he was able to compare the reliability, as quantified by a Defect Detection Probability (DDP), of various inspection procedures. Figure 9 shows the results for 4 techniques.

FIGURE 8. Signal as a function of position for smooth crack.
A number of related activities were also undertaken in the UK that extended the modeling base developed at CEGB. At the UKAEA facility in Harwell in the 1985-1991 time period, Ogilvy developed a model for the ultrasonic inspection of rough cracks in which Kirchhoff scattering theory was applied to idealized crack surfaces [14].

Similar concepts were later used at CEGB [12] in a “triangular facet” model, see Fig. 10, that included a beam model and the effects of calibration. Other important work in the UK included the work of Ogilvy on ultrasonic propagation in anisotropic,
inhomogeneous media such as are found in austenitic welds (leading to the code RAYTRAIM); the work of Temple on modeling time of flight tip diffraction, diffraction coefficients in anisotropic media, reflection and transmission at surfaces and the use of finite difference modeling codes; and the work of Gould and Firth on a hybrid finite difference/Helmholtz integral model for ultrasonic scattering.

CONCLUSIONS

Since the 1980’s, modeling has played an important role is assessing NDE reliability. It is interesting to note the complementary paths taken in the UK and US, as illustrated in Table 1.

This work has strongly influenced capabilities under development and in use today such as European requirements for assessing inspections for nuclear reactors (ENIQ), American-led efforts in the development of procedures for Model-Assisted Probability of Detection (MAPOD) and commercially available codes that support these activities.

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