한국공작기계학회 2003 춘계학술대회 논문집 pp.73~78

IMPROVED POD METHODOLOGY USING MONTE CARLO SIMULATION

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Abstract

Ultrasonic measurement is one of important technologies in the life-time maintenance of nuclear power plant. Ultrasonic inspection system is consisted of the operator, equipment and procedure. The reliability of ultrasonic inspection system is affected by its ability. The performance demonstration round robin was conducted to quantify the capability of ultrasonic inspection for in-service. The small number of teams who employed procedures that met or exceeded ASME Sec. XI Code requirements detected the piping of nuclear power plant with various cracks to evaluate the capability of detection and sizing. In this paper, the statistical reliability assessment of ultrasonic nondestructive inspection data using Monte Carlo simulation is presented. The results of the probability of detection (POD) analysis using Monte Carlo simulation are compared to these of logistic probability model. In these results, Monte Carlo simulation was found to be very useful to the reliability assessment for the small hit/miss data sets.

INTRODUCTION

Throughout the world, most nuclear power plants (NPP), as well as chemical and petroleum plants, have been in operation beyond their original design lives of 30 to 40 years. Nondestructive evaluation (NDE) techniques for characterizing important mechanical and material conditions, such as structural support integrity and pressure boundary defects at weld locations in NPPs, have been developed and implemented through various initiatives. The safety, reliability, and cost effective operation and maintenance of NPPs are based on the effectiveness of NDE.

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It is well known that in-service inspection (ISI) plays an important role in assuring the integrity of a structure or component of NPPs. The pre-service inspection (PSI) and ISI in Korean NPPs are performed according to ASME code Section XI every 10-year period during the plant operation, because the ASME code mandates that PSI/ISI be performed by NDE.

The ultrasonic inspection system consists of the operator, equipment and procedure. The reliability of results in UIS is affected by its ability. It is reported that frequently existing ISI UT methods can not detect even quite large defects in mock-up specimens, fail to size the defect, and are dependent upon an inspector's skill and physical condition. Furthermore, the reliability of ultrasonic ISI is influenced by the inspection environment, other materials and types of defect. Therefore, it is very difficult to estimate the reliability of NDE due to various factors.

In current practice, the POD curve is normally given by an assumed distribution function which can be characterized by a few free parameters that are determined by empirical tests[3]. However, if POD is obtained through the use of models, then no distribution shape need be assumed a priori. In analysis of a large number of nondestructive size data, a linear relation between the logarithm of a measured flaw size and the logarithm of the true flaw size with normally distributed deviation has proved satisfactory[1]. In typical NDE reliability studies, relatively few inspections are performed on each flaw in the specimen set. The small number of samples which are typical of field inspection data lead to two types of problems with POD models. It is possible to have a sample which is not a good representation of the actual population, giving rise to poor estimate of POD. And, the confidence levels on the POD-flaw size relationship are often extremely broad for small sample sizes.

In this paper, the performance demonstration round robin was conducted to quantify the capability of ultrasonic ISI and to analyze the level of ISI UT technology in Korea. For the sake of the statistical reliability analysis of round robin test results, studied the model of the reliability of assessment such as logistic probability model and investigated the feasibility of Monte Carlo simulation. The results of the Monte Carlo simulation are compared to these of probability of detection analysis using logistic probability.

STATISTICAL RELIABILITY DATA ANALYSIS

Round Robin Test

The round-robin test was conducted in 2001 at the KINS to qualify the capability of ultrasonic inspection for in-service and to address some aspects of reliability for this type of NDE. Two inspection groups participated in the round robin -- a total of 9 companies that comprised 15 commercial inspection teams employed by commercial in-service inspection companies. An individual team (consisting of level Ⅱ and Ⅲ inspectors) conducted ultrasonic examinations on welded pipes. Two different types of flaws were implanted into the specimens (EDM notchs and thermal fatigue cracks (TFCs)). The round-robin measured the detection and sizing capabilities of fifteen inspection teams who employed procedures that met or exceeded ASME Code Sec. XI requirements. The specimens are inspected under conditions that simulate as closely as practical the actual application conditions. Tabulated sheets were provided for the tested personnel to keep their records. POD curves are also constructed for each company and/or their participating personnel. Superiority of the NDE performance for the participating companies as well as their personnel was thus revealed. Figure 1 shows the procedure of reliability analysis of round robin test results.

POD Models

The fundamental definition of probability of detection is that the ratio of the number of flaws detected by a given technique to the total number of actual flaws present in the inspected components. POD is a well established measure of inspection performance that is directly related to important issues such as accept-reject criteria, frequency and quality of inspection, etc.[2].

In recent years, an approach based on the assumption of a model for the POD function was devised[4-5], many people have assumed that repeated inspections are statistically independent events that increase the chance of detecting flaws and therefore improve POD. Spencer[6] proposed an extension to the curve-fitting method of estimating POD. The Spencer model includes terms to account for false call and miss rates that are independent of flaw size. Analysis of data from reliability experiments on NDI methods indicated that the

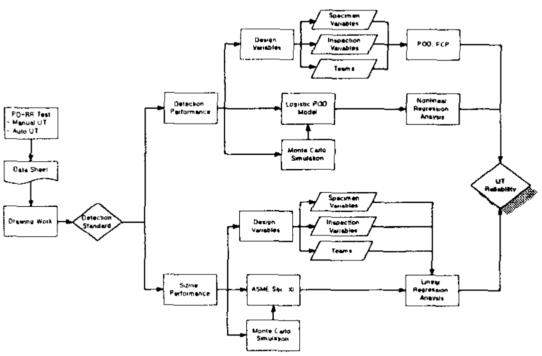


Figure 1. The procedure of reliability analysis of round robin test

POD function can be reasonably modeled by the cumulative log normal distribution function or, equivalently, the logistics function. The parameters of these functions can be estimated using maximum likelihood methods. The statistical uncertainty in the estimate of NDI reliability has traditionally been reflected by a lower(conservative) confidence bound on the POD function. The asymptotic statistical properties of the maximum likelihood estimates can be used to calculate this confidence bound. In this study, the logistic POD function is adopted. A mathematically equivalent form of the logistic POD model is given by[1]:

$$POD(a) = \left\{ 1 + \exp\left[-\frac{\pi}{\sqrt{3}} \left(\frac{\ln a - \mu}{\sigma} \right) \right] \right\}^{-1} \qquad (1)$$

in this form, $\mu = \ln a_{0.5}$, where $a_{0.5}$ is the flaw size that is detected 50% of the time, that is, the median detectable crack size. the steepness of the POD function is inversely proportional to σ. The parameters of POD function are related by $\mu = (-\alpha/\beta)$, $\sigma = (\pi/(\beta/\sqrt{3}))$. The logistic POD function is practically equivalent to a cumulative lognormal distribution with the same parameters, μ and σ of POD function. This POD function is the form of the logistic model that will be used analysis of hit/miss data in thes study.

Monte Carlo simulation

The primary objective of NDE reliability experiments has been to demonstrate efficacy for a particular application by estimating the POD function and its lower 95% confidence bound. In general, the specimens used in NDE reliability experiments are very expensive to obtain and characterize in terms of the sizes of flaws in the specimens. Therefore, each experiment is based on a number of sets of specimens containing flawed and unflawed inspection sites. Because the results are significantly influenced by the specimens, it must be assumed that the flaws are representative of those that will be present in the structural application. If other factors are to be included in the experiment, they will be based on repeated inspections of the same flaws.

From a statistical viewpoint, data from hit/miss experiments are generally not amenable to testing assumptions regarding the form of the POD model. These tests require either large numbers of independent inspections on each flaw of a specimen set or inspection results from an extremely large number of compatible specimens[3]. Number and size considerations in hit/miss experiments are directed at their effect on the parameters of the POD function.

To overcome the problem of having a small number of hit/miss data sets, the reliability assessment of ultrasonic NDI data using Monte Carlo simulation is useful. For the statistical POD simulation, one must estimate the probability density function (PDF) which is suitable for the characteristics of detection probability. As shown in Figure 2, POD is expressed when the inspector detects a crack as a hit(1) and not as a miss(0), and assumed as a triangular distribution using the results obtained from the repeated inspections of the same flaw. The PDF of β-distribution is defined as:

$$y = f\left(x \middle| a,b\right) = \frac{1}{B(a,b)} x^{a-1} (1-x)^{b-1} I_{(0,1)}(x) \qquad (2)$$

The statistical properties of the maximum likelihood estimates can be used to calculate the variables a, b. Figure 3 shows the β-distribution depending on the values of the parameters. We can generate 100 times simulated random number depending on β-distribution by using Matlab Statistics Toolbox, and effectively get 100 times detection test results for each crack.

Reliability Data Analysis

Under usual field environment, POD shows various spectrum. Design variables of a test are those which defines conditions of tests and materials influencing spectrums of such various conditions. Here, a variable is a discrete independent variable which does not influence other variables. Figure 4 shows a plot of the logistic function showing detection performances of all the teams. This is the result of detection skill of ultrasonic test in Korea. As crack size increases, detection probability increases. POD curves were constructed to plot the relationship of POD to crack depth and length as the independent variables, using mathematical regression techniques

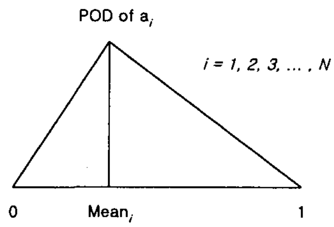


Figure 2. Triangular distribution

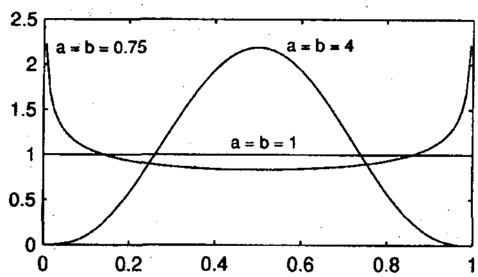
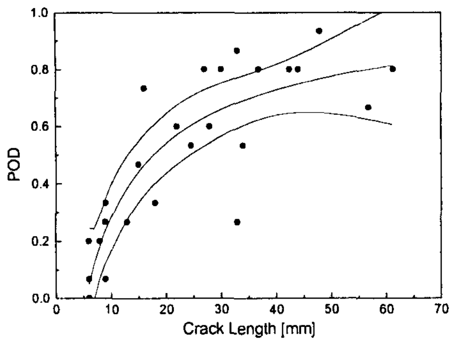
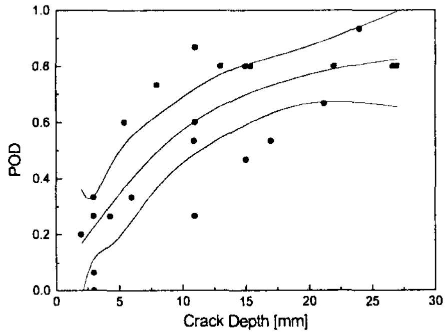


Figure 3. β-distribution depending on the values of the parameters

to fit the curve to the experimental data. The logistic curves are surrounded by 95% confidence bounds and the raw POD points used in the fit are illustrated on the plots.

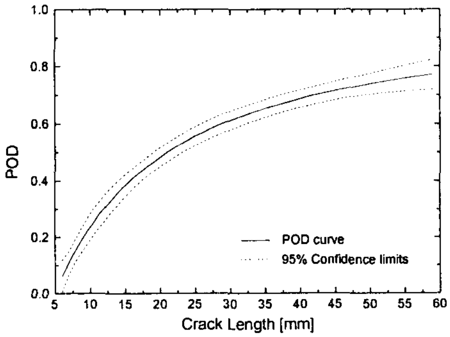


(a)

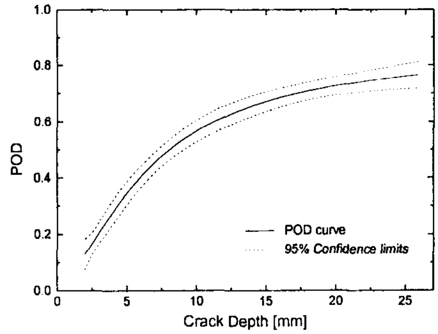


(b)

Figure 4. Logistic curve fit to POD data with 95% bounds(All teams) (a) POD vs length, (b) POD vs depth



(a)



(b)

FIGure 5. Logistic curve fit to POD data from Monte Carlo simulation with 95% bounds (a) POD vs. Length (b) POD vs. Depth

Each POD point describes the detection results on an individual defect in round robin. Figure 5 shows the logistic curve fit to POD data from Monte Carlo simulation with 95% bounds (a) POD vs. Length (b) POD vs. Depth. It is well known that the ideal detection probability graph is such one that the width of 95% confidence interval is narrow and POD is close to 1 from small crack. Compare to the results of the logistic model, the Monte Carlo simulation algorithms gave similar results to the previously published algorithms, but, the width of 95% confidence interval is narrower. In these results, statistical analysis of POD hit/miss data using Monte Carlo simulation was found to be very feasible to the reliability assessment of the small number of NDE data sets.

Conclusions

In this paper, the statistical reliability assessment of ultrasonic inspection system using Monte Carlo simulation is presented. The results of the Monte Carlo simulation are compared to these of probability of detection analysis using logistic probability. The Monte Carlo simulation algorithm gave similar results to the previously published algorithms, but the width of 95% confidence interval is narrower. In these results, statistical analysis of POD hit/miss data using Monte Carlo simulation was found to be very feasible to the reliability assessment of the small number of NDE data sets.

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