Reliability Analysis of Pipe Suffering Wall Thinning Based on Quantification of Nondestructive Evaluation Uncertainties

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URL	http://hdl.handle.net/10097/00135878

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学位論文題目　Reliability Analysis of Pipe Suffering Wall Thinning Based on Quantification of Nondestructive Evaluation Uncertainties (非破壊評価の不確実性の定量化に基づく減肉を受ける配管の信頼性分析)

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論文内容要約

Carbon steel pipes are widely employed in nuclear power plants to transfer water, steam, or a mixture of both. Indeed, the pipelines are prone to metal loss mainly due to flow accelerated corrosion and liquid droplet impingement, leading to pipe wall thinning. Without proper maintenance, pipe wall thinning can give rise to pipe failures, such as leakage and rupture. Therefore, an effective maintenance strategy is necessary to maintain pipe integrity and mitigate pipe failure.

The codes of pipe wall thinning management have been issued in Japan. The management utilizes nondestructive evaluation (NDE) to inspect pipe using the ultrasonic testing method and derive the information on pipe wall thinning from inspection data. According to the technical rules, the target piping systems and locations to be inspected are selected in terms of the susceptibility to wall thinning, which is evaluated based on operation conditions. The remaining service life of pipe is predicted with wall thinning rate for planning the inspection timings. The wall thinning rate is primarily determined based on past inspection data, which requires enormous inspection works and repeatable inspection conditions as the variation of inspection conditions, e.g., the variation of instrumentation, the misalignment of inspection location in consecutive inspections, will have adverse effect on the accuracy of the estimation of thinning rate.

The prediction models of pipe wall thinning developed based on corrosion/erosion mechanism and/or empirical data can help to reduce the volume of inspection. With the help of the prediction models, the pipe segment susceptible to wall thinning can be identified and the pipe status affected by wall thinning can be assessed. The prediction results of pipe wall thinning will be leveraged to determine inspection location and timing. However, the prediction models may be prone to large uncertainty due to insufficient understanding of thinning mechanism, simplification of the models, and random variation of the input variables. NDE can be employed to reduce the model uncertainty of prediction models. The model parameters are tuned by NDE data through Bayesian method to calibrate the prediction models for more accurate prediction of pipe wall thinning growth.

Conventional pulse-echo ultrasonic testing (UT) is the commonest NDE technique adopted in nuclear power plants for measuring pipe wall thickness. In spite of its high accuracy in gauging thickness, the requirement of removal of insulation, pipe surface preparation, couplant, and manual operation significantly impairs its efficiency and consequently causes a high cost of time. Early studies also proposed a non-contact, low frequency electromagnetic method (LFEM) testing method to inspect carbon steel pipe suffering wall thinning. Its mechanism is similar to that of the conventional MFL testing method, while saturated magnetization is not required. In contrast, the

magnetization is held at its initial stage due to a weak magnetic field applied. The magnetic property of the carbon steel can thus be kept within the linear range. In addition, this method can exploit coherent detection techniques to increase the signal-to-noise ratio. Our group has investigated the influences of some parameters on the signal response of the LFEM testing method, confirmed its capability to detect wall thinning in carbon steel pipes, and developed a mapping method to estimate the size of wall thinning based on simulated signal response. Hence, the experimental and simulation environments of the LFEM testing method are available.

The processes of NDE are affected by various aleatory factors, which will result in uncertainty in detecting and sizing wall thinning. The detection uncertainty refers to that a flaw is not detected despite its presence, or noise is mistaken for the positive indication of a flaw. The sizing uncertainty, i.e., sizing error, means the deviation of estimated flaw size from actual flaw size. In fact, NDE inevitably suffers both detection uncertainty and sizing uncertainty. NDE uncertainty can propagate through the procedures of pipe reliability analysis, such as pipe thinning rate estimation and pipe remaining service life prediction, and finally, lead to a large error in pipe reliability assessment. However, the NDE data is treated deterministically in the management without considering the NDE uncertainty. Thus, more reasonable pipe wall thinning management needs to be developed to take NDE uncertainty into consideration. In addition, quantification methods of NDE uncertainty are necessary so that NDE uncertainty can be quantitatively considered in pipe reliability analysis.

The study aims to develop quantification methods of detection uncertainty and sizing uncertainty for the inspection of pipe wall thinning and incorporate the quantification into pipe reliability analysis.

This study was carried out on the basis of a low frequency electromagnetic (LFEM) testing method whose capability to detect and size wall thinning on the inner surface of carbon steel pipes has been preliminarily investigated in previous studies. The signal response of the LFEM testing method due to pipe wall thinning was analyzed using finite element simulation and experiment. The governing equation for simulating the inspection of pipe wall thinning, a magnetoquasistatic problem, was derived from Maxwell’s Equations, based on which the finite element simulation was implemented using commercial software. Simulation models were individually built for pipe with fully circumferential wall thinning and for pipe with local wall thinning. The experimental systems of LFEM testing were constructed to inspect carbon steel pipe samples containing artificial wall thinning of different profiles. A signal processing method was proposed to normalize the signal response. It is confirmed that the normalization can suppress the effect of certain variables unrelated to the flaw and enhance signal features associated with pipe wall thinning. Finite element simulations were conducted to investigate the influences of several variables on the normalized signal response, such as excitation frequency, relative permeability of pipe material, lift-off, and flaw edge profile. By examining the effect of excitation frequency, the axial magnetic flux density component of 1 Hz was chosen to be used for the detection of wall thinning. The variation of relative permeability of pipe can be a major source of noise in the signal response. In contrast, the variation of lift-off has a minor contribution to the noise. The edge profile of the flaw was confirmed that it has a significant effect on the signal response in terms of amplitude and profile of signal response.

The quantification method of detection uncertainty was developed based on monitoring pipe wall thinning using the LFEM testing method with permanently installed sensors. The detection uncertainty is supposed to be affected by not only multiple flaw parameters but also sensor placement. A multi-variable POD model was thus developed to quantify the detection uncertainty with the help of numerical simulation. Discrepancy exists between simulated signal response and measured signal response because the signal response is unavoidably affected by the change of wall thickness varying within manufacturing tolerance, inhomogeneity of the magnetic permeability of the pipe material, misalignment of the magnetic sensors, seamless pipe noise, and so on, and all of the influential factors are commonly present in practical inspection; moreover, not all influential factors in practical inspection can be quantitatively considered in numerical simulation. A probabilistic calibration model was proposed to evaluate the discrepancy with limited experimental data. Experimental verification confirms that the calibration model is able to evaluate the discrepancy and calibrate simulated signal response. The distribution of measured signal response can be inferred based on simulation data for determining POD using Monte-Carlo method. The generated POD contours have been proved able to correctly reflect the effect of multiple parameters of wall thinning and sensor placement on the detection uncertainty.

A quantification model was developed based on a probabilistic machine learning algorithm, Gaussian Process Regression, to estimate the residual thickness and axial length of pipe wall thinning and quantify the sizing uncertainty. The signal features of multi-frequency (1 Hz, 5 Hz, 10 Hz, and 15 Hz) signal features that are strongly correlated with flaw parameters were extracted as input variables. The machine learning algorithm demands large and realistic training data to make sure the estimation results of flaw sizes are reliable. A multivariate normal model was then developed to characterize the joint distribution of the signal features based on simulated signal features and the consideration of the correlation among the signal features of the same frequency. The effectiveness of the model was examined by contrasting the estimated joint distribution with measured signal features. The estimated joint distribution was leveraged to quickly and economically generate training data for the algorithm using Monte-Carlo simulation. It has been demonstrated that the trained algorithm is able to estimate both axial length and residual thickness of wall thinning with tolerant error. The robustness of the inverse algorithm was also investigated, which suggests that the estimation error of residual thickness does not change significantly in spite of the changes of lift-off and circumferential angle of wall thinning. Moreover, the algorithm has the potential to estimate the residual thickness corresponding to different circumferential locations accurately. By analyzing the estimation results of GPR, it is suggested the estimation errors are related to the corresponding residual thickness. A linear model was proposed to relate the estimation errors with the estimated values of residual thickness in order to quantify the sizing uncertainty.

A pipe reliability analysis framework that can incorporate the quantification of detection uncertainty and sizing uncertainty of NDE was developed. In the pipe reliability analysis framework, the prediction models of wall thinning were KWU-KR model for the depth, gamma process model for the axial length, and uniform distribution for the circumferential angle. A limit state function of the three flaw parameters was adopted to estimate the pipe strength and decide the pipe failure. A hierarchical Bayesian network was built to represent the conditional relationship among variables. Accordingly, a Bayesian model was formulated to incorporate the developed multi-variable POD model and the quantification model of sizing uncertainty to infer the parameters of prediction models of wall thinning growth with NDE data. A case study was used to demonstrate the implementation of pipe reliability analysis.