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論文内容要旨

In nuclear power plants (NPPs) of both types of pressurized water reactor (PWR) and boiling water reactor (BWR), huge number of pipes are employed for the transportation of coolant water and steam. Local wall thinnings such as flow accelerated corrosion (FAC) and liquid droplet impingement (LDI), may happen at the inner surface of the pipe wall due to the long time of fluid flowing. FAC is a degradation mechanism of pipe wall due to dissolving of a normally protective oxide layer on the metal surface in a fast flowing fluid. The underlying metal corrodes to re-create the oxide which causes metal loss, i.e., corrosion. If this process continues a very long time, eventually the remaining wall thickness may become insufficient to subject the internal pressure and may lead to a rupture event. LDI is another wall thinning mechanism caused by fast liquid droplet in the inner pipe wall surface. From the fast water or steam flow in the coolant water/steam pipes of the nuclear power plants, the liquid droplets may repeatedly shock the inner tube surface. The corresponding shock and collision force will damage the tube wall, and cause wall thinning gradually. The LDI often occurs in the curvature part or orifice region of the pipe as the inertia shock of liquid droplet happens frequently in these positions. Due to LDI, even through holes may be formed together with the increment of the wall thinning depth. Although there is sufficient safety margin in the designed pipe wall thickness, wall thinning defect may lead to bad consequences out of imagination if it becomes very serious. Some pipe failure accidents caused by the wall thinning problem, such as the Mihama accident 2004, have been reported recent years in NPPs around the world. This requires the pipe wall thinning defect in NPPs to be regularly inspected and quantitatively assessed in order to guarantee the safety.

Since the wall thinning (FAC/LDI) occurs at the inner side of the pipes, a nondestructive testing (NDT) technique is necessary to investigate the status of the inner surface of the pipes. In view of the features of different NDT methods, the pulsed eddy current testing (PECT) method is considered as one of the promising NDT techniques for the pipe wall thinning inspection and on-line monitoring without removing the insulation outside the pipe. In addition, quantitative evaluation of the wall thinning defect is indispensable in order to make proper maintenance activity once a wall thinning defect is detected.

Therefore, the feasibility evaluation of quantitative NDT (QNDT, i.e. profile reconstruction) of pipe wall thinning defect using PECT method is very important, and it is selected as the main objective of this study.

The principle of the PECT technique is similar with the conventional ECT method from the viewpoint of defect detection. Electromagnetic induction phenomenon is the basis of both the PECT and ECT for detecting flaws in conductive materials. The different point of PECT from the conventional ECT method is that it employs pulsed excitation current instead of the sinusoidal one applied in the conventional ECT method. The pulsed signal contains rich harmonic frequency components, fruitful information in time slice, and much larger current amplitude can be applied comparing with that of the conventional ECT. These features make the PECT applicable to detect deep buried defect or far side defect in a thick inspection target. Recently, research activities are conducted on the further theoretical and technical development of PECT, such as the defect detection, material property characterization and defect reconstruction etc. However, more studies are still necessary in the enhancement of PECT technology especially on the response signal interpretation, detectability improvement, and quantitative flaw reconstruction. It is well known that numerical analysis is a useful approach for better understanding and further development of the PECT technology. Among the numerical techniques, a high efficient (high accuracy and low computer burden) numerical tool for PECT signal prediction and a stable inverse analysis scheme of high reliability are strongly expected to realize the defect QNDT with PECT signals.

Based on these backgrounds, the objectives of the dissertation are mainly on the following two aspects: 1) development of an efficient numerical simulation tool for the forward signal prediction of PECT technique; 2) development of inversion algorithm for the inverse analysis of PECT and feasibility assessment for QNDT of pipe wall thinning in NPPs using PECT method. This thesis summarizes the theories and results of the research topics described above. The whole volume consists of seven chapters, and is organized in the following order:

In Chapter 1, the detailed research backgrounds, state of the arts of the ECT and the PECT technologies, and the major research objectives of this thesis are described.

In Chapter 2, the basic theory and numerical formulation of some conventional methods for ECT signal simulation are given for reference of the later chapters. The basic formulation, the numerical discretization procedure, and the signal calculation formulae of the $\boldsymbol{A}$ - ϕ method based FEM-BEM hybrid code and the $\boldsymbol{A}_r$ method based edge element FEM code are introduced respectively.

In Chapter 3, PECT experimental system developed in the present study is described at first, and its validity is verified through comparing the measured and simulated PECT signals. Second, the influence of some experimental parameters such as the fundamental frequency, duty factor of the pulsed excitation and the type of the pickup elements (pickup coil, Hall sensor and Flux Gate sensor) on the PECT signals are investigated in order to optimize the PECT system. In addition, a new feature parameter is originally proposed for the PECT signals and its efficiency is validated by processing the measured PECT signals. At last, the feasibility of the developed PECT system is demonstrated for the quantitative pipe wall thinning evaluation through inspection experiments of three typical kinds of test-pieces with local wall thinning (double-layer structure plate, double-layer structure pipe and elbow).

In Chapter 4, a Fourier-series-based numerical method combined with an interpolation strategy is proposed for the forward prediction of PECT signals based on the finite element method. The number of frequencies used in the summation and the selection of harmonic frequency components used for the interpolation, which are very important for the simulation accuracy, are thoroughly discussed in this part. Second, a code of direct time-domain integration (TDI) method for PECT signal prediction is presented. Next, the comparison of the numerical simulation results and experimental results is performed to demonstrate the accuracy and efficiency of the proposed methods. Finally, PECT signal of local wall thinning in pipe configuration, which is difficult to be solved by the analytical simulation approach, is simulated using the proposed numerical methods.

In Chapter 5, a very fast numerical solver is originally developed for efficient simulation of PECT signals due to volumetric defects by introducing the database type fast ECT simulation scheme to the Fourier-series-based PECT signal simulation code given in Chapter 4. At first, the database type fast solver for signal prediction of single frequency sinusoidal ECT is upgraded to treat the volumetric defects (local wall thinning). In order to cope with the fast PECT signal simulation of 3D local wall thinning defect, a 2D shifting symmetry scheme (shown in Fig. 1) is proposed for inspection targets of plate and straight pipe geometry to reduce the computational burden to be used to establish databases of the unflawed field, which are necessary for the fast ECT signal simulation. Then, the fast PECT solver for volumetric defects is developed based on the Fourier series method and this fast simulation scheme for single frequency ECT. Comparison of the numerical results and the experimental results demonstrated that the proposed fast PECT solver can significantly reduce the simulation burden (100 times faster) for local wall thinning problem but without losing numerical accuracy. The present work gives a good basis for the inverse analysis of the PECT signals due to pipe wall thinning defect.

In Chapter 6, an inversion algorithm for sizing of 3D wall thinning defect is proposed and implemented based on the developed fast PECT simulator and a deterministic optimization strategy. First, the principle of the conjugate gradient (CG) inversion scheme and the parameterization strategy of wall thinning defect are described, and an inversion code is developed based on these theories for sizing of local wall thinning. Equation (1) shows the formula to calculate the gradient vector from the calculated electric fields for the transmitter-receiver type PECT probe and Eq. (2) shows the feature extraction from the signal of the transient gradient vector (t_0 is peak time). Second, several reconstruction examples are performed for both simulated and measured PECT signals to investigate the validity and the robustness of the proposed inversion scheme (Fig. 2 shows one reconstruction result from the measured PECT signals). In addition, a neural network (NN) type method is also given in this chapter for the reconstruction of local wall thinning together with some validation results using simulated PECT signals for comparison. Through investigation, it is found that both the CG optimization strategy and the NN based inversion algorithm can efficiently reconstruct the simple shape local wall thinning defect, though the reconstruction accuracy of the latter one is slightly lower than the former one.

$$\frac{\partial B(\boldsymbol{r},t)}{\partial c_{w,i}} = -\sigma_0 \sum_{n=1}^{N} F_n \left(\alpha \int_S \boldsymbol{E}_p^u \cdot (\boldsymbol{E}_e^u + \boldsymbol{E}_e^f) \frac{\partial s_w(\boldsymbol{c},\boldsymbol{r})}{\partial c_{w,i}} ds \right) e^{j\omega_n t} \tag{1}$$

$$\frac{\partial P(\boldsymbol{r})}{\partial c_{w,i}} = \left.\frac{\partial B(\boldsymbol{r},t)}{\partial c_{w,i}}\right|_{t=t_0} \tag{2}$$

The general conclusions and some prospective aspects are given in Chapter 7. As a summary, the major achievements of this study are as follows, 1) an efficient numerical simulation method based on Fourier series method, database type fast forward solver and interpolation of frequency response function is originally developed, and is proved very fast and high accuracy for PECT signal simulation through comparing with the experimental results. 2) Inversion algorithms and the corresponding numerical codes using CG and NN methods for PECT technique are originally developed, and proved suitable for reconstruction of local wall thinning defect in inspection target of complicated geometry from PECT signals. The combination of these two inversion algorithms can be prospective to improve the inversion results further.

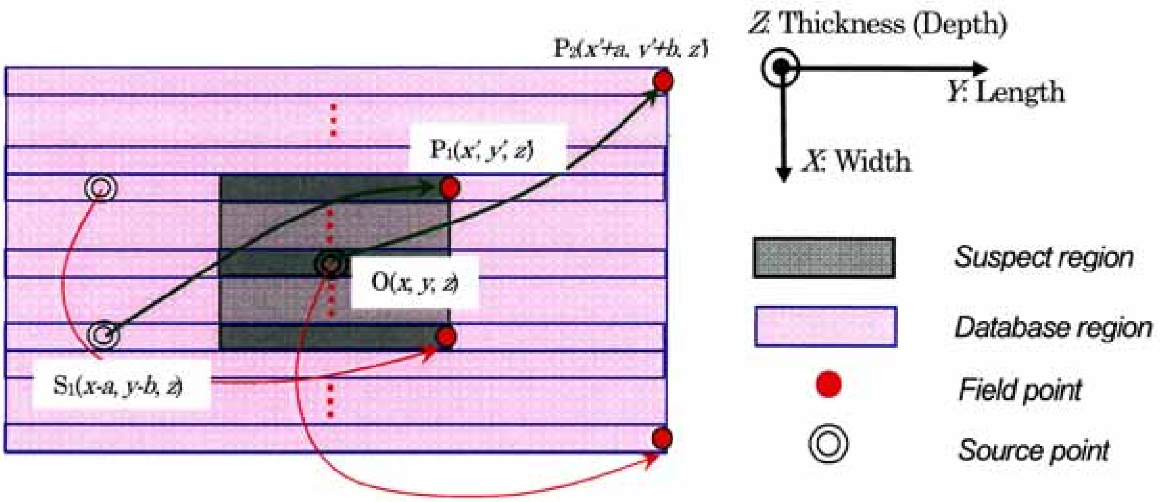
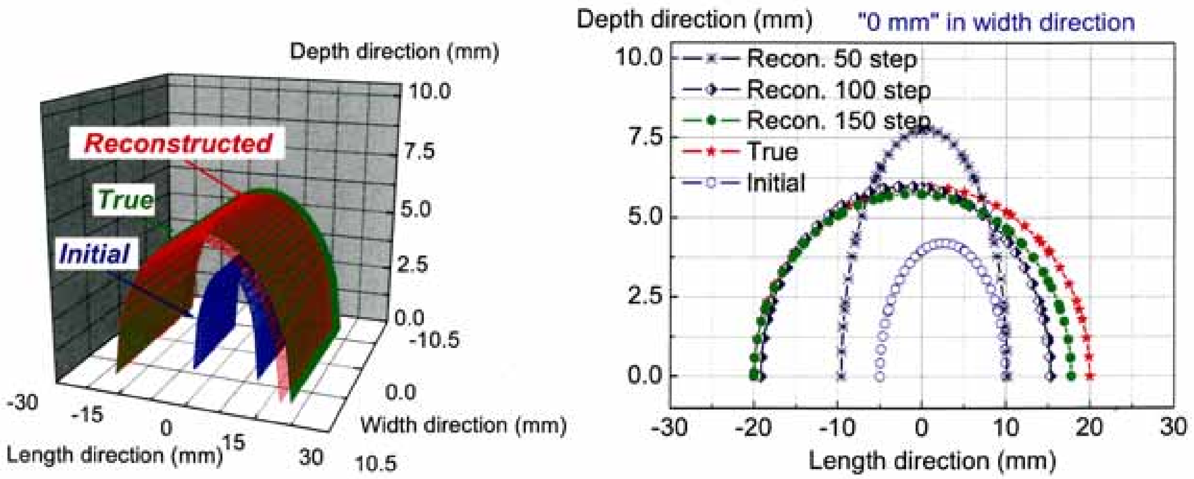


Fig. 1 The principle of the 2D shifting symmetry scheme



(a) 3D wall thinning shape; (b) Cross-section, "0 mm" plane in width direction

Fig. 2 Wall thinning shape: true, initial and reconstructed

論文審査結果の要旨

原子力発電所や火力発電所などの発電プラントや，化学プラント等の多数の配管を持つプラントでは，配管内を流れる冷却材などにより生じる配管内面の減肉の管理が重要な課題である。配管の局部減肉は配管の破損などを引き起こし，プラントの安全性に深刻な影響を及ぼすため，定期的に配管の肉厚を非破壊的に測定することが必要である。これらの配管肉厚は，通常は超音波厚さ計により測定するが，補強板がある二層配管では，超音波試験のような従来の非破壊検査手法では検査が困難である。また，配管の厚さのみでなく欠陥の形状を知る方法が求められている。本研究の目的は，この問題を解決するために電磁現象を用いた渦電流探傷法の一種であるパルス渦電流探傷法（PECT）について実験および解析の両面から研究することである。研究内容と成果は以下の三点である。(1)パルス渦電流探傷法の実験装置を開発し，二層配管の内側の欠陥の検出可能性を示す。(2)信号の予測のための高精度で高速の数値計算解析法を開発する。(3)配管肉厚の定量評価のために逆問題解析の手法を提案して，配管肉厚の評価を実施する。本論文は、これらの研究成果をまとめたものであり，全編7章からなる。

第1章は序論であり，本研究の背景，課題，目的および構成を述べている。

第2章では，渦電流探傷信号解析に従来用いられていた手法について基礎的な理論とその定式化を示している。有限要素法(FEM)と境界要素法(BEM)を複合化したコードを基とする A-ϕ法および辺要素を用いた FEM に関する定式化と離散化，信号処理のための定式化について述べている。

第3章では，PECT の実験信号と解析信号の比較からその実験装置の検証について述べている。パルス信号の基本周波数やデューティ比に重点を置き，検出器の選定と共に，実験条件の最適化を行っている。また，実験により得られた信号の処理に関して，減肉に対して最も優位に変化するパラメータを提案し，減肉試験片の測定結果から検証している。これは重要な知見である。

第4章では，順問題解析のために，フーリエ級数を用いた解析手法に周波数領域での定式化を用いて計算時間短縮のための内挿スキームを組み込んだ解析手法を提案している。特に，解析精度に直接的に影響を及ぼすフーリエ級数の周波数の数および周波数の選択法について議論している。PECT 信号予測の解析コードを開発し，実験と数値解析の比較によって解析コードの妥当性について確認している。従来困難とされてきた配管形状の減肉信号の予測に成功しており，重要な成果である。

第5章では，データベースを用いた渦電流探傷解析スキームを拡張し，フーリエ級数を基としたパルス渦電流信号解析コードに導入することで，計算精度を低下させることなく，計算時間を 100 分の 1 に短縮している。これは、計算の効率を大幅に向上させたという点で非常に重要な成果である。

第6章では，前章で開発したPECT信号の高速シミュレータと，共役勾配法(CG法)およびニューラルネットワーク(NN)を用いた方法に基づき，3次元形状の減肉のサイジングのための逆問題解析アルゴリズムを構築している。実験信号を用いて逆問題解析を実施し，CG 法および NN 法のどちらにおいても減肉形状の再構成ができることを示し，CG法がNN法に比べやや高い精度で減肉を再構成できることを示している。逆問題解析による定量的な減肉形状の再構成に成功した点において，非常に重要な成果である。

第 7 章は結論であり，本論文を総括している。

以上要するに本論文は，配管減肉の検出およびサイジングの課題に対して，電磁現象を用いた非破壊評価法の一種であるパルス渦電流探傷法を用い，実験および解析の両面から減肉評価の可能性について詳細に検討を重ねており，多くの重要な知見を示していることから，非破壊検査手法の高度化に大きく貢献するものであり，バイオロボティクスおよび機械工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。