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論 文 内 容 要 旨

For the engineering judgment based on the quantitative non-destructive evaluation (NDE), it is of primary importance to determine the geometrical features of flaws in the infrastructure. The reliable method using the low frequency ultrasonic wave needs to be developed for the flaw imaging. In this thesis, the linearized inverse scattering methods based on the Born and Kirchhoff approximations are investigated to reconstruct the size, shape and orientation of flaws from the scattered ultrasonic waveforms in the relatively low frequency range. The abilities of the Born and Kirchhoff inversions are simulated first by numerically calculated scattering amplitudes with the boundary element method (BEM), then confirmed by experimentally measured waveforms. For applications to the actual field of NDE, the following points are discussed:

(1) Fast inversion
(2) Flaw type classification
(3) Multi-point measurements

This thesis is composed of 7 chapters. The schematic flow-chart of this thesis is shown in Fig.1. Each chapter is summarized as follows.

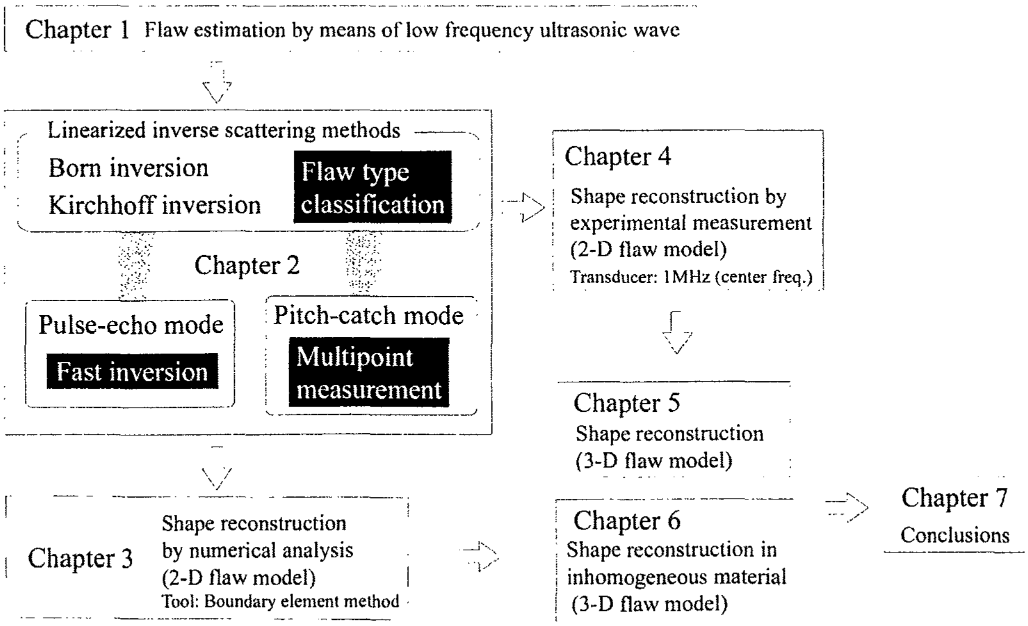

Fig.1: Outline of this thesis

1. Introduction

When the ultrasonic testing is applied to the infrastructures such as concrete structures, the ultrasonic waves in high frequency range are attenuated. Since the primary advantage of the ultrasonic wave is the ability to penetrate into the deep part in solid, the quantitative method using the low frequency ultrasonic waves needs to be developed for the flaw imaging in infrastructures. As imaging techniques for flaws in an elastic material, the linearized inverse scattering methods are investigated in this thesis. The historical background of the linearized inverse methods is shown in this chapter.

2. Linearized Inverse Scattering Methods

The unified two (2-D) and three dimensional (3-D) elastodynamic inversions are formulated in this chapter. These methods are based on the Born and Kirchhoff approximations for unknown displacements in the integral representation of the scattering amplitude. Born inversion reconstructs the characteristic function Γ which represents the inside of flaws, and Kirchhoff inversion reconstructs the singular function γ which has the value only on the boundary of flaws. From the formulations of two inversions, it is found that the only difference of the Born and Kirchhoff inversions is a factor $\{ik_\alpha\}$, where k_α is the wave number of type α = L or T (L: longitudinal, T: transverse). The factor $\{ik_\alpha\}$ can be interpreted to be the difference of filters in Born and Kirchhoff inversions. The combined use of Born and Kirchhoff inversions leads to the classification of flaw type between crack like flaw and volumetric flaw.

Born and Kirchhoff inversions are expressed for two types of transducer configurations, one is the ultrasonic pulse-echo mode and the other is the pitch-catch mode. The pulse-echo mode can be carried out with the fast inversion technique. The pitch-catch mode is applied to the multi-point measurements for the sake of the highly accurate inversion. The usefulness of the fast inversion and the accurate inversion with the multi-point measurements is discussed in the numerical simulations in Chapter 3 and the experimental measurements in Chapter 4.

3. Inversions by Numerical Analysis

The shape reconstructions of flaws are demonstrated by the numerically calculated scattering amplitudes with the BEM. Here, 2-D flaw models are tested by the ultrasonic pulse-echo and pitch-catch modes. It is verified that the Born inversion can reconstruct the inside of flaws and the Kirchhoff inversion can the boundary of flaws. The Born inversion can be applicable not only for the weak scatterer but also for the strong scatterer like a cavity. Since the Kirchhoff approximation is based on the reflection at the flaw surface, the combination of the Kirchhoff inversion and the pitch-catch mode provides the effective tool for the shape reconstruction. From the numerical results, it is also found that the shape of flaw can be reconstructed when the incident beam with the sufficiently wide radius stimulates the flaw.

The fast inversion, flaw type classification, multi-point measurements are simulated, and the versatilities of the techniques are confirmed in this chapter.

4. Inversions by Ultrasonic Measurement

The shape reconstruction of flaws is verified with the experimentally measured waveforms by the L-L pulse-echo and the L-L pitch-catch modes. Aluminum specimens including the 2-D artificial flaws are prepared and the scattered waveforms from the flaws are measured. To extract the scattering amplitude data from the scattered waveforms, a data processing based on the linear time-shift invariant system is proposed by means of the reference wave from a hole.

When the incident wave is transmitted from one side of the specimen, the illuminated side of flaw can be reconstructed. And it is shown that the scattered wave components in the low frequency range are essential for the shape reconstruction of flaws in the present methods.

5. Shape Reconstructions of 3-D Flaws

The 3-D linearized inverse scattering methods are investigated for the shape reconstructions of flaws in the 3-D elastic body. The performance of the 3-D linearized inverse scattering method is examined first by the numerically calculated backscattering amplitude. Then a 3-D flaw model in an aluminum specimen is reconstructed with the measured backscattered waveforms.

For the practical use of 3-D inversion, the 3-D inversion formulas are modified in order to reconstruct the cross-sectional view of flaws from the backscattered waveforms obtained at a measurement section. The cross-sectional views of the reconstructed image show that the inversion with the wide incident beam gives the representative flaw size and the narrow beam gives the cross-sectional image of the flaw.

6. Macroscopic Flaw Reconstruction in Inhomogeneous Material

A shape reconstruction method of the macroscopic flaw in an inhomogeneous material is proposed by taking into account of the order of scales for the flaw, inhomogeneities of the material, and the wavelength of the elastic wave. The frequency dependency of the phase velocity due to the inhomogeneity of the material is introduced into the inversion algorithm. The frequency dependency of the phase velocity is estimated by the Kramers-Kronig relation with the numerical analysis. The effect of the volume fraction of the inhomogeneities on the shape reconstruction is discussed with the two specimens, one is 5% and the other is 10% volume fractions. In this inhomogeneous model, the image resolution of the flaw reconstruction for the specimen with 5% volume fraction is superior to the flaw with 10% volume fraction.

7. Conclusions

The summary of each chapter and conclusions are described in this chapter. The following three points were investigated for application of the linearized inverse scattering method throughout in this thesis. These were examined by the numerical analysis and the usefulness is verified by the experimental measurement.

(1) Fast inversion

The principal operation of the linearized inverse scattering method is the integration of scattering amplitudes in the K-space, where K-space consists of the wave number and the observation angle. Here the FFT is introduced into the integration of the inversion algorithm.
The computational time of the inversion is dramatically improved without loss of the image resolution (see Fig.2).

	Rough estimation of calculation(multiplications)	Calculation time
Numrical integration (Gauss-Legendre quadrature)	measurement direction($d\theta$): 36 wave number (dk_L): 100 Gauss-Legendre rule: 4point × 4point output interval(Δx_a): 40 × 40 $36\times 100\times 4^2\times 40^2=9.216\times 10^7$(times)	35.937sec
Fast technique (2D-FFT)	**$N_1=N_2=128$** **$(N_1N_2/2)\log_2(N_1N_2)=1.147\times 10^5$(times)**	**0.049sec**
$\frac{\text{Fast technique}}{\text{Numrical integration}}$	$\frac{1.147\times 10^5}{9.216\times 10^7}=\frac{1}{803.5}$	$\frac{0.049}{35.937}=\frac{1}{733.5}$

(CPU:Compaq Alpha 21264 667MHz(Dual), RAM:512MB)

Fig.2: Performance of the fast inversion technique.

(2) Flaw type classification

The Born inversion is sensitive to the volumetric flaw but not to the crack-like flaw. On the other hand, the Kirchhoff inversion reacts to both boundaries of volumetric and crack-like flaws (see Fig.3). From these results, the combined use of Born and Kirchhoff inversions is proposed to discriminate the crack from the volumetric flaw. It is confirmed that the procedure of this flaw classification works effectively for experimentally measured waveforms.

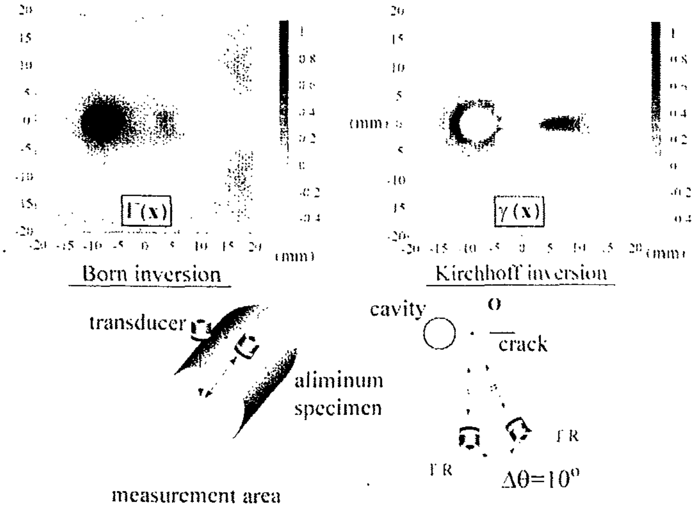

Fig.3: Shape reconstruction of a cavity and an artificial crack by measured waveforms in the frequency range 0.1~1.8MHz (L-L pulse-echo mode).

(3) Multi-point measurements

The multi-point measurements are introduced into the inversion for the pitch-catch mode. The multi-point measurements are achieved by switching the transmitting points, and the geometrical functions obtained for each transmitting point are superposed to perform the shape reconstruction. Even if the dynamic interaction effects of flaws are included in the measured waveforms, it is possible to reconstruct the flaw shape with the high accuracy (see Fig.4).

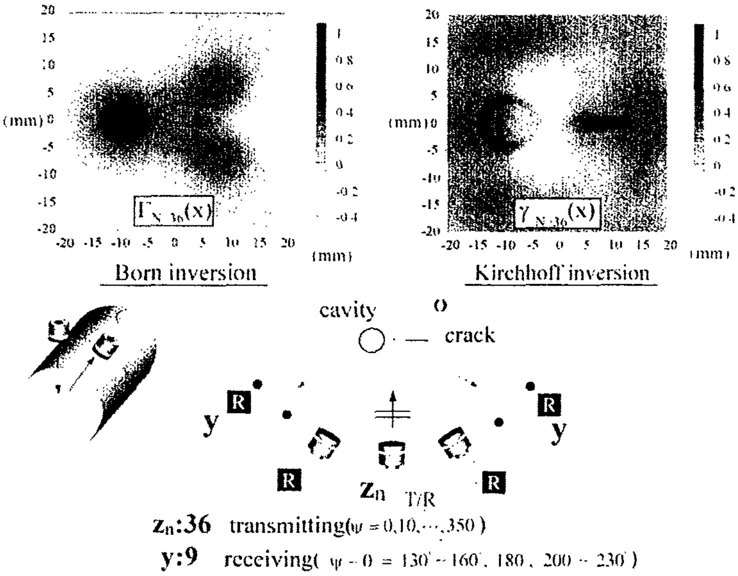

Fig.4: Shape reconstruction of a cavity and an artificial crack by measured waveforms (multi-point measurement).

論文審査結果の要旨

土木構造物に対して超音波を用いた非破壊評価を行う場合、構造物の大規模性と非均質性に起因して波動の高周波成分は減衰するため、低周波数域の波動を用いた部材内欠陥の定量的な評価法が求められている。本論文は、欠陥による散乱波から逆に欠陥形状を再構成する線形化弾性逆散乱解析法の形状再構成能を、低周波数域波形成分の役割に着目して明らかにし、非破壊評価への応用を示したものであり、以下の7章により構成される。

第1章は序論であり、本研究の背景、目的、線形化逆散乱法に関する既往の研究、本論文の構成を述べている。

第2章は二次元および三次元弾性波動場における線形化弾性逆散乱解析法の定式化である。具体的には、空洞状欠陥とき裂状欠陥の識別を意図して、欠陥領域を再構成するボルン逆散乱解析と欠陥境界を再構成するキルヒホフ逆散乱解析を定式化している。ここで、両逆散乱解析共に超音波パルスエコーモードとピッチキャッチモードに対応している。パルスエコーモードは高速化手法によりリアルタイム処理が可能となり、ピッチキャッチモードは多点計測との組み合わせにより高精度再構成が可能となる。対象とする欠陥の評価に要求される検出精度に応じて二つのモードを使い分けることを提唱しており、現実の非破壊検査への応用を考える上で有用な成果である。

第3章は境界要素法を用いて、数値解析による欠陥再構成シミュレーションを行っている。この結果から、ボルン逆散乱解析は欠陥の内部を、キルヒホフ逆散乱解析は欠陥の境界を再構成することを示している。また、欠陥に対して十分に大きなビーム径を有する入射波が送信されておれば、欠陥形状が正確に再構成できることを明らかにしている。これは、両逆散乱解析法によれば超音波ビーム径を絞ることなく形状再構成が可能であることを意味しており、低周波数域超音波が有効に活用できる根拠となる重要な結果である。

第4章は超音波計測実験を行い、計測された散乱波から逆に人工欠陥像を再構成している。ここで提案したデータ処理法を基にして散乱波形から散乱振幅データを抽出し、両逆散乱解析に入力すれば、計測散乱波形から欠陥像の再構成が可能であることを確認している。また、計測波形を用いた逆散乱解析において、欠陥寸法と同オーダー以上の散乱波の波長成分が欠陥再構成に大きく寄与していることを明らかにしている。これは、散乱波の低周波成分が欠陥像の再構成に重要であることを意味しており、低周波数域超音波を活用する上で有用な知見である。

第5章は前章までの結果を踏まえて、三次元欠陥像の再構成を試みている。数値解析と計測実験により、線形化逆散乱解析法が三次元欠陥に対しても良好に機能していることを示している。また、既存の構造物を考えて、計測点が部材の一側面に限られた場合に対応するために、三次元逆散乱解析法の一側面計測への拡張を行い、その有用性を検証している。

第6章は非均質材料中の欠陥形状再構成への応用を示したものである。定式化の過程において、位相速度の周波数依存性を逆散乱アルゴリズムに組み込んでいる。非均質体中の空洞状欠陥による散乱波から逆に欠陥形状の再構成が可能であることを示したことは、土木構造物への低周波数域超音波の適用を考える上で重要な成果である。

第7章は結論であり、本研究で得られた主要な結果をまとめている。

以上要するに本論文は、部材内欠陥を再構成するために低周波数域超音波を活用した弾性逆散乱解析法を構築し、数値解析および計測実験の両面からその有用性を検証すると共に、非破壊評価への応用について検討したものであり、土木工学および超音波非破壊検査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。