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学 位 論 文 題 目	Development of Damage Diagnostic Technique for Mercury Target Vessel of　High-power Spallation Neutron Source Using Ultrasonic Waves (超音波を用いた高出力核破砕中性子源水銀ターゲット容器の損傷診断技術の開発)
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論 文 内 容 の 要 旨

High power spallation neutron sources are being developed in the world. Liquid metal is used as the target material from the viewpoints of neutron yield and cooling capability. Mercury target for spallation neutron source has been installed at MLF (Materials and Life science experimental Facility) in J-PARC (Japan Proton Accelerator Research Complex). However, various kinds of damages, such as cavitation damage, fatigue damage and irradiation damage, are imposed on the target vessel during operation of the mercury target. The remote noncontact diagnostics that can correspond to the high radiation environment is strongly expected for the in-situ evaluating the lifetime of the target.

The objectives of this thesis are to evaluate micro-scale and macro-scale cavitation damages and to develop the in-situ diagnostic technique for monitoring the structure integrity of mercury target vessel. In the present study, the nonlinear ultrasonic and laser ultrasonic techniques were applied for cavitation damage evaluation. Based on the basic knowledge obtained by the ultrasonic techniques, the effects of cavitation damage on the dynamic responses of mercury target vessel were investigated.

The thesis consists of six chapters.

In Chapter 1, the background of issues relating to structural integrity in the mercury target is introduced. Then the cavitation damage and the proposed ultrasonic techniques are mentioned. Some issues related to the study on ultrasonic inspection are summarized. Objectives and structure of thesis are given in Chapter 1.

In Chapter 2, the nonlinear ultrasonic technique was used to evaluate the cavitation damage considering its sensitivity to defects. The resonance and nonresonance methods were adopted for evaluation, respectively. The dependency of vibration amplitude on cavitation damage evaluation was systematically investigated. The results showed that the generation of higher harmonics was dependent on the vibration amplitude, and the resonance method could effectively evaluate the damage which attributes to the stronger higher harmonics generation.

However, the procedure for nonlinear ultrasonic damage evaluation is not established up to now. Regarding this issue, the dependencies of ultrasonic parameters (cycles and frequency) on cavitation damage were systematically investigated in Chapter 3. Based on the results, a novel procedure was established for cavitation damage evaluation by using ultrasonic waves. The mechanisms of ultrasonic attenuation and higher harmonics generation due to damage were combined to establish the evaluation procedure. The results showed that the evaluation procedure could effectively and accurately evaluate cavitation damage. It can also be applied for evaluating various surface and sub-surface micro defects in materials.

In Chapter 4, on the basis of the knowledge obtained by nonlinear ultrasonic, the laser ultrasonic technique was adopted to evaluate artificial cavitation damage. A laser beam was used to impact the specimen and to simulate the bombardment of proton beams as well. The specimen vibration was remotely monitored by a Laser Doppler Vibrometer (LDV). Meanwhile, the numerical simulation was carried out using Wave3000, a commercial Finite Difference Method code, to quantitatively study the dependency of ultrasonic wave propagation behavior on damage. It was found that the ultrasonic propagation behavior is closely related to the pitch and depth of pits in the cavitation damage. The diagnostic technique based on the propagation behavior of the ultrasonic wave was developed and the cavitation damage was quantitatively evaluated by the laser ultrasonic technique.

In Chapter 5, the vibrational signals of double-walled target vessel were applied for evaluating the structural integrity that will be affected by cavitation damage. An electro-Magnetic IMpact Testing Machine (MIMTM) was used to experimentally simulate the structure of double-walled vessel which is excited impulsively and repeatedly through mercury. The vibration of MIMTM was measured in noncontact and remotely by using a LDV system. The numerical simulations were carried out by the LS-DYNA, a Finite Element Method code, to systematically investigate the dependency of damage on the vibration behavior of double-walled vessel. Considering the size of the target vessel, macro-scale cavitation damage was assumed on the inner wall of target vessel. Furthermore, Wavelet Differential Image (WDI) was proposed as a diagnostic technique to clearly detect the differences of vibration signals dependent on cavitation damage. The statistical methods referred to as Analysis of Variance (ANOVA) and Analysis of Covariance (ANOCO) were used to reduce the noise. The results showed that the vibration behavior was dependent on the damage. In the case of micro-scale damage, the differences of the vibration signals that caused by damage trended larger with increasing the peak-to-peak roughness of cavitation damage. While in the case of macro-scale damage, the differences of the vibration signals that caused by damage trended larger with increasing the diameter of cavitation damage.

Brief summary of each chapter is given in Chapter 6. In this study, the relationships between ultrasonic waves and cavitation damage were investigated. As a result, the fundamental knowledge that is necessary to establish the diagnostic technique for evaluating the structure integrity caused by damage was established through this study. It can be concluded that：

1. When ultrasonic waves transmit through or reflected from cavitation damage, there was attenuation and induced nonlinearity of transmitted or reflected waveforms. The attenuation was mainly caused by the scattering from the cavitation damage; the induced nonlinearity was caused by the “Clapping” and “Friction” of interfaces of micro cracks at the bottom of the cavitation damage. Higher harmonic components were generated due to the nonlinearity of transmitted or reflected waveforms. By making use of the attenuation and higher harmonic components, the established novel evaluation procedure successfully evaluated tiny pits combined with micro cracks.
2. For the laser ultrasonic evaluation, the amplitude of converted shear waves and the attenuation of transient resonance vibration caused by longitudinal waves were closely related to the pitch and depth of pits in the cavitation damage. It was considered that the cavitation damage reduces the effective thickness of specimen. The propagation distance of converted shear waves from source to detector was shortened due to the reduction of effective thickness of specimen. Cavitation damage with peak-to-peak roughness of at least 15 μm was successfully evaluated by the laser ultrasonic technique.
3. The vibration behavior of target vessel was dependent on the cavitation damage. In the case of micro-scale damage, the vibration behavior of target vessel was related to the reduction of effective thickness of specimen due to the cavitation damage; while in the case of macro-scale damage, the vibration behavior of target vessel was related to the pressure waves that propagated through the penetrated damage.

論文審査の結果の要旨

（独）日本原子力研究開発機構では、高エネルギー加速器研究機構と共同で、平成20年度から世界最高レベルの大強度陽子加速器施設（J-PARC）を稼働している。J-PARCを利用することで、原子核・素粒子物理研究、中性子を用いた物質・生命科学、さらには高レベル放射性廃棄物中の長寿命核種を短寿命の核種に変換する技術開発など、広範な研究分野で新たな進展が期待されている。本学位論文は、J-PARCで用いられている核破砕中性子源水銀ターゲット容器に関して、超音波を用いた損傷診断法を開発し、容器の寿命予測や高健全性容器設計に資するための研究成果をまとめたものである。とくに、キャビテーション損傷に着目し、放射能環境における遠隔、その場診断法の確立を目指している。

第1章では、本論文の背景と目的ならびに論文の構成について述べている。

第2章と第3章では、キャビテーション損傷の非線形超音波診断法に関して、核破砕中性子源水銀ターゲット容器材料であるSUS316Lの損傷に及ぼす超音波パラーメータを系統的に調べ、振動の減衰特性と損傷に起因する高調波特性から、マクロスケールから25 μm程度のマイクロスケールまでの損傷を同定できることを明らかにしている。

第4章では、前章の知見をレーザ超音波診断に拡張した。人工的に損傷を付与したSUS316L試料にレーザ光を照射して超音波を励起させ、さらにレーザドップラー計でモニタリングし、その波形から損傷のアスペクト比やピットの深さを定量的に評価する遠隔非接触診断法を開発している。また、Wave3000コードを用いた数値シミュレーション法により、損傷の有無による超音波の伝播挙動の違いを明らかにするとともに、ウェーブレット解析を併用する方法を提案している。これにより最大高さ粗さ15 μm程度の損傷まで診断精度を向上させることができることを明らかにしている。

第5章では、新型の二重壁構造ターゲット容器を対象として、電磁衝撃試験装置MIMTMを用いた水銀中でのキャビテーション実験を行い、得られた損傷試料に対して前章までに得られたレーザ超音波診断の手法が適用できるかどうかを検証し、その有効性と適用限界を明らかにしている。さらに、LS-DYNAによる数値シミュレーションとウェーブレット解析の併用により、超音波の伝播挙動の解明や損傷の可視化にも成功している。

第6章では、本研究を総括して、結論を述べている。

学位論文内容は、学術誌論文4編（第1著者4編、うち掲載済2編、掲載待2編）、その他5編（第1著者5編、発表済）として公表または公表予定である。レーザドップラー法を用いた故障診断法はすでに提案されているが、本学位論文では、J-PARCで使用されているSUS316L製ターゲット容器のキャビテーション損傷を対象に、非線形超音波診断法を提案している。とくに、数値シミュレーション法とウェーブレット解析の併用により、損傷の有無による超音波の伝播挙動の違いを明らかにするとともに、損傷の診断精度を大幅に向上させている。また、電磁衝撃試験装置MIMTMを用いて作製したキャビテーション損傷試料に対して、提案したレーザ超音波診断手法の有用性を検証している。これらの成果は、ターゲット容器の寿命予測や高健全性容器設計に資するだけでなく、高放射線場など特殊環境下における遠隔、その場診断法としても活用することができる。

審査会及び最終試験の結果、本学位申請は、博士（工学）の学位を授与するに十分な内容と認められるので、合格と判定する。