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Proposal of Shear-Wave-Excited Evanescent Super-Resolution Imaging Method for the Detection of Micro Defects and Its Fundamental Study
微小欠陥検出のための横波励起エバネッセント超解像映像法の提案と基礎検討

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1. Introduction

Super-resolution imaging beyond the diffraction limit using evanescent fields has been studied not only in electromagnetics[1)] but also in acoustics and ultrasonics. In acoustics, holey-structured acoustic metamaterials (HSAMs) have been proposed for super-resolution geometry measurement.[2,3)] As shown in **Figure 1(a)**, its application to nondestructive testing was also proposed for super-resolution imaging of subsurface micro defects.[3)] This is based on the resonance of longitudinal waves in HSAM, resulting in bright-field imaging. However, the signal-to-noise ratio (SNR) was insufficient because of the spreading of the incident wave. Further, an achievable resolution is limited by the machining accuracy for HSAMs.

This study proposes a novel super-resolution imaging method of utilizing the mode-converted longitudinal evanescent field (MCL-EF) generated by a shear horizontal (SH) plane wave incidence. This method is dark-field imaging, improving an SNR without using HSAMs. Further, the image resolution is not limited by the hole size of HSAM. Although MCL-EF was theoretically predicted for a flat interface,[4)] its generation around defects has yet to be examined. Hence, we first examined its generation around a simple defect, a small hole, with numerical simulation and experiment, followed by the numerical simulation for more realistic defects.

2. Principle of Super-Resolution Imaging Method based on MCL-EF

We propose a super-resolution dark-field imaging method of utilizing both longitudinal and shear waves, i.e., MCL-EF. As illustrated in **Figure 1(b)**, an SH plane wave is transmitted into a specimen. The wave transmitted through the specimen is measured by a laser Doppler vibrometer (LDV)[4)] during its scanning. In a defect-free region, no response is observed since LDV measures only out-of-plane displacements, which are perpendicular to the vibration direction of the SH wave. In a region with subsurface defects, an MCL-EF is generated in the vicinity of the defects when the incident angle at the interface of defects is greater than a critical angle determined by

$$\theta_{\mathrm{iSHcr}} > \sin^{-1}(v_{\mathrm{SH}}/v_{\mathrm{L}}) \,, \qquad (1)$$

where v_{L} and v_{SH} are the speeds of longitudinal and SH waves in the specimen, respectively. The MCL-EF can be generated even if they are much smaller than the wavelength. Note that MCL-EF has an out-of-plane displacement in contrast to the incident SH wave. Hence, the measurement of out-of-plane displacement by LDV for SH plane wave incidence gives super-resolution dark-field imaging. This method does not require HSAMs. The spatial resolution can be enhanced from the hole size of HSAMs to an LDV scan pitch (~ tens of μm).

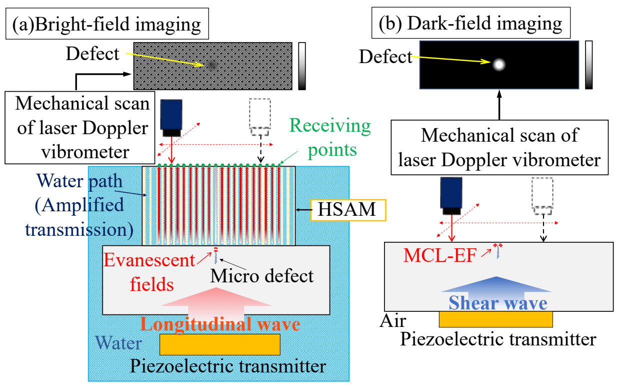

Fig. 1 Super-resolution imaging method.

3. MCL-EF in the vicinity of a small hole

To examine the generation of MCL-EF in the vicinity of a simple defect, a small hole, we performed a numerical simulation using an FEM (finite element method) software, ComWAVE. As shown in **Fig. 2**, we modeled a small hole with ϕ 0.15 mm (≈ λ/20). An SH plane wave (1 MHz, 3 cycles) with a horizontal displacement was inputted upward.

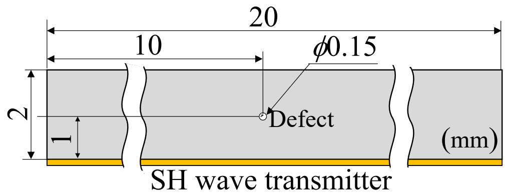

Fig. 2 FEM model with a small hole.

Figure 3(a) shows the simulation results. In a defect-free region, no longitudinal-wave component was observed for the SH-wave incidence. In a region in the vicinity of the hole, a spatially localized MCL-EF was observed. Interestingly, the responses were strong in the oblique regions to the incident direction, which is in good agreement with the theoretical predictions for satisfying Eq. (1) and Ref. (4).

To validate the FEM simulations, we carried out a fundamental experiment in an A7050 plate with a small hole (ϕ1 mm). A shear wave transducer (ϕ15 mm, 1 MHz) was in contact with the side surface of the specimen to input an SH plane wave. The LDV scan was done over 10 × 10 mm^2 with a pitch of 0.5 mm while inputting the SH wave.

To examine the MCL-EF, we extracted the peak from the out-of-plane displacement waveforms at each measurement point. As a result, a strong MCL-EF in four oblique regions was observed. Although the responses were not symmetric probably because of the machining accuracy of the hole, the MCL-EF (**Figure 3(b)**) qualitatively agreed well with the FEM results (Figure 3(a)). Thus, we confirmed the generation of MCL-EF near micro defects and validated the FEM simulation for this application.

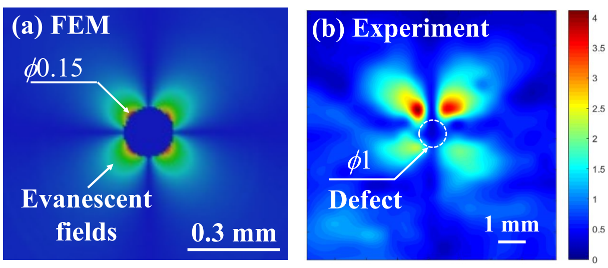

Fig. 3 Out-of-plane displacement around a hole.

4. FEM simulation in realistic defects

We conducted the FEM simulation to examine the MCL-EF for more realistic defects: a crack with rough faces (0.03 mm wide and 1 mm long) and unbonded region. We transmitted SH plane waves upward. **Figure 4** shows the simulation results of MCL-EF around the defects. Different patterns appeared depending on the defect geometries. We found that the change in the defect geometry was the source of the MCL-EFs. It can be understood by assuming that a part of the defects locally satisfied Eq. (1). It also suggests that the proposed method can be applied to natural defects.

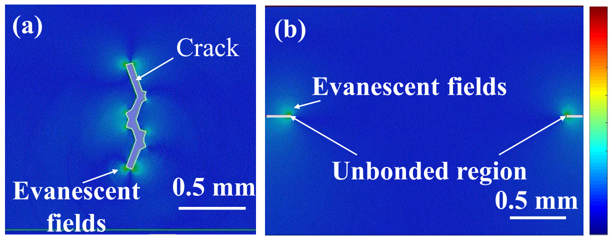

Fig. 4 Numerical simulation of MCL-EF in the vicinity of realistic defects.

5. Conclusion

To markedly improve the detection limit and SNR of the conventional method using HSAM, we proposed a super-resolution dark-field imaging method of utilizing MCL-EF. To prove the concept, we examined the MCL-EF in the vicinity of a small hole by FEM and experiments. We also investigated the MCL-EFs in more realistic defects. The results were in good agreement with theoretical predictions. On the other hand, we observed the MCL-EFs on the planes with the defects. However, such planes cannot be accessed for practical application. Further, one-side access would be desirable. These are some of the topics that we will work on in the future.

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References

1. J. B. Pendry: PRL, **84** (2000) 3966.
2. J. Zhu, et al.: Nat. Phys., **7** (2011) 52.
3. S. Laureti, et al.: Sci. Rep., **10** (2020) 10601.
4. K. K. Amiredy, et al.: Sci. Rep., **7** (2017) 7777.
5. L. M. Brekhovskikh, V. Goncharov: *Mechanics of Continua and Wave Dynamics* (1994) pp. 59-65.
6. Y. Ohara, et al.: APL, **117** (2020) 111902.