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A theoretical approach to multiple scattering of surface waves by shallow cavities in a half-space

Haidang Phan [a], Younho Cho [b,*], Weibin Li [c]

[a] Institute of Mechanics, Vietnam Academy of Science and Technology, 264 Doi Can, Ba Dinh, Hanoi, Viet Nam
[b] School of Mechanical Engineering, Pusan National University, 2, Busandaehak-ro, 63beon-gil, Geumjeong-gu, Busan 609-735, South Korea
[c] Department of Aeronautics, Xiamen University, South Siming Road, 361005 Xiamen, China

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ABSTRACT

The current theoretical work investigates multiple scattering of surface waves from shallow cavities at the surface of an elastic half-space. The multiple scattered field is shown to be equivalent to the field generated by the application of a distribution of tractions, obtained from the incident wave, on the surfaces of the cavities. Using a self-consistent method, an analytical approach is proposed to derive an explicit set of equations which approximate the multiple scattered field. Its far-field displacement amplitude is then calculated and verified by numerical calculation obtained by the boundary element method (BEM). The analytical and BEM results are graphically presented and show excellent agreement when the depths of cavities are small compared to the wavelength. The improvement of the proposed approach relative to a first order approximation is reported and its limitations are discussed based on the results of comparison.

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1. Introduction

In practice, several defects may appear close to each other in engineering structures making it extremely difficult or impossible for any ultrasonic nondestructive evaluation (NDE) technique to examine each defect separately. Therefore, a more realistic problem, multiple interaction of an ultrasonic wave with an area containing a number of defects, is essential to be investigated. When surface of structure appears with a group of defects such as cavities, grooves, cracks or canyons which are not accessible for visual inspection, surface waves can be very useful in the detection and characterization of defects.

Due to mechanical or chemical conditions, undesirable damage in the form of parallel scratches or cavities may occur on the surface of structures. The propagation of plane strain waves will then be perturbed by the cavities. Thus, it is important to understand multiple scattering phenomena of surface waves by cavities in order to gain more information about the characteristics of cavities and structures.

Multiple scattering is an important and interesting topic of relevance in a wide variety of physical contexts. In general, it means "the interaction of fields with two or more obstacles". If there are numerous obstacles, the field scattered from one obstacle will induce further scattered fields from all the other obstacles, which will induce further scattered fields from all the other obstacles, and so on [1]. For the problem of an incident field scattered by a random distribution of obstacles, the question is how to compute multiple scattered field once solution for scattering by a single obstacle has been obtained.

Scattering of surface waves from defects has received much attention from physicians and seismologists over the past decades. Model for scattering of surface waves by a defect has been extensively studied by various investigators. Typical examples of analytical work are the papers by Abrahams and Wickham [2], Gilbert and Knopoff [3], Ogilvy [4], Tuan and Li [5] and recently by Phan et al. [6,7]. Numerical work has been investigated by the use of the finite element method; see Hassan and Veronesi [8], and the boundary element method; see Arias and Achenbach [9] and Liu et al. [10]. Several advanced numerical methods have recently developed for wave propagation in functionally graded materials, for example the articles by Golub et al. [11], Hedayatrasa et al. [12], and Fomenko et al. [13].

There are a number of authors who have studied scattering of elastic wave by several defects. Simons [14] considered Rayleigh wave reflection by periodic arrays of strips and grooves. Scattering of an obliquely incident wave by an array of spherical cavities was investigated by Achenbach and Kitahara [15] while Angel and Achenbach [16] studied the problem with cracks. Interaction of

* Corresponding author.
E-mail address: mechcyh@pusan.ac.kr (Y. Cho).

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harmonic waves with a periodic array of cracks was worked by Mikata and Achenbach [17] and Scarpetta and Sumbatyan [18]. These works, however, ignored the multiple scattering effect.

While numerous authors have worked on the scattering of elastic wave by defects, there have been much fewer that have studied them in the context of multiple scattering. Martin and Maurel [19] and Linton and Martin [20] used an approach similar to the one we adopt here, which dates back to Foldy [21]. Martin calculated an effective wavenumber for second order approximation of scattered field. Cheng [22] and Varadan et al. [23] considered multiple scattering of elastic waves by parallel cylinders. Preliminary analytical results of multiple scattering of surface waves by cavities were reported in [24]. Recently, multiple scattering of Lamb waves by corrosion pits in a plate was carried out by Strom et al. [25]. Taheri and Honarvar [26] investigate the multiple scattering of acoustic waves from a network of cylindrical rods embedded in a viscoelastic medium for applications in nondestructive testing of composite materials.

The current paper introduces a novel analytical approach, which may be referred to as a second order approximation, to multiple scattering of surface waves by shallow cavities. One of the main contributions is that we derive an explicit set of equations which approximate multiple scattered field. This results in simple calculations of multiple scattered field. In addition, computations obtained by the proposed method show improvement in comparison with results from a commonly-used first order approximation.

This approach is, in principle, applicable for both surface and subsurface cavities of arbitrary shape. To determine the advantages and the limits of applicability of the proposed method, however, we consider a relatively simple configuration of scattering by circular cylindrical cavities at the surface of a half-space. In the current investigation, the self-consistent method [1] is employed in combination with the single scattering result [6] to derive a set of equations which lead to solution of scattered displacement field. Numerical calculations based on the boundary element method are obtained in order to verify analytical solution. Comparisons between analytical and BEM results are graphically displayed and it is followed by discussion on the limitations of the proposed method. It is also reported in this article the enhancement of the present approach relative to a first order approximation.

The found analytical solution provides a fast and computationally inexpensive approximation to the multiple scattering problem. An understanding of multiple scattering phenomena allows us to perform and adjust ultrasonic tests on an interactive basis, thus providing us with an effective response process to improve data acquisition. Scattering of surface waves from a random arrangement of cavities can also be used for gaining more information about the characteristics of cavities and structures. The backscattered waves contain valuable information that can be used for characterization of the cavities.

The description of the article proceeds through eight sections. The problem is stated as linear superposition of the incident wave and the scattered field in Section 2. It follows by Section 3, representation of self-consistent method for the purpose of surface wave scattering. Section 4 reviews scattering of surface waves from a single cavity. Model for multiple scattering of surface waves by two-dimensional cavities is presented in Section 5. Here, calculations of displacement amplitudes of back-scattered and forward-scattered surface waves are derived. Multiple scattering of surface waves from a periodic array of cavities is studied in Section 6. Section 7 briefly describes the use of BEM technique for solving multiple scattering problem. Section 8 shows the comparisons between analytical and BEM results and is followed by discussion. Section 9 states the conclusion.

2. Problem statement

A homogeneous, isotropic, linearly elastic solid occupying the half-space $z \geqslant 0$, relative to a Cartesian coordinate system (x, y, z), contains a group of circular cylindrical cavities distributed randomly on the surface of the half-space in the $x, z-$ plane. A plane surface wave propagating in the positive $x-$ direction is incident on the cavities so that it can be considered as a two-dimensional problem (Fig. 1). The interaction of the surface wave with the cavities generates a multiple scattered field of surface waves which is of interest in this paper.

By virtue of linear superposition, multiple scattered field is equivalent to the field generated by the application of distributions of horizontal and vertical tractions on the surface of the cavities, see Fig. 2. These tractions are equal in magnitude but opposite in sign to the corresponding tractions due to the incident wave on virtual cavities in the half-space without cavities. Thus, the horizontal and vertical tractions can be calculated from the stress components of the incident Rayleigh wave and the outward normal vectors of the cavity surfaces by using Cauchy's formula.

For the case of numerous cavities, the field scattered from one cavity will induce further scattered fields from all the other cavities, which will induce further scattered fields from all the other cavities, and so on. The summation of these scattered fields results in the multiple scattered field which eventually includes a back-scattered surface wave and a forward-scattered surface wave as shown in Fig. 2. The concept of multiple scattering comes from the recursive way of thinking about how to calculate the scattered displacement in which each step is called an order of scattering.

3. Self-consistent method

Assuming that we know everything about scattering of surface waves by a single cavity in isolation, the question is how to use this knowledge to solve a more complex but more practical problem, the multiple scattering of surface waves from cavities. It is a good idea to use a self-consistent method. According to Martin [1], the total field u_{to} can be written as

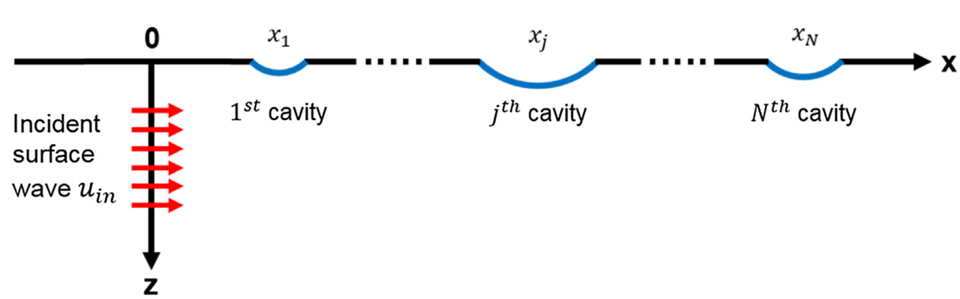

Fig. 1. Multiple scattering by two-dimensional cavities.

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