INVESTIGATION ON THE DIRECTIVITY OF ULTRASONIC SCATTERING FIELD USING DYNAMIC PHOTOELASTIC TECHNIQUE

Zhi-wu AN[1,*], Shi-jie JIN[1,2], Guo-xuan LIAN[1], Xiao-min WANG[1]

[1] State Key Laboratory of Acoustics, Institute of Acoustics, Chinese Academy of Sciences, Beijing 100190
[2] NDT & E Laboratory, Dalian University of Technology, Dalian, 116085
[*] Corresponding author, E-mail: anzhiwu@mail.ioa.ac.cn; Tel.: 86-10-82547763.

A dynamic photoelastic imaging system is presented and employed to study the directivity of ultrasonic scattering field. Focusing on the cylindrical cavity, photoelastic photograph displays the scattering field, and the directivity patterns of different distances can be plotted by the gray level per pixel. Compared with the simulation results by finite element method (FEM), dynamic photoelastic technique shows more reliable directivity patterns which are in close proximity to the practical scattering field.

Keywords: Ultrasonic scattering field; Directivity; Dynamic photoelastic technique; Cylindrical cavity

1. INTRODUCTION

Ultrasonic scattering fields in solid have been widely investigated [1-4]. The directivity patterns can not only point out the energy distribution in the scattering field, but also reveal some characteristics of the acoustic source or the obstacle [5-8]. As a result, it has drawn much attention. Guan and Norris [5] studied the elastic waves scattering by a rectangular crack and discussed the influence of incident direction to the directivity patterns. White [2] presented the far-field directivity patterns of the scattering field at a cylindrical discontinuity both in theory and experiment. However, the experiment result was measured point by point, which is very complicated, and hard to display the backwards directivity, while the theoretical results often ignore the influence of transducer, which will bring errors especially in the near-field. To solve these problems, the dynamic photoelastic technique is considered to obtain the complete directivity patterns.

Dynamic photoelastic technique, whose physical basis is temporary birefringent effect, is an experimental method to investigate stress or stress waves. This method was firstly used to study the stress fields, mainly static, in solid structures since the 1920s, and extended to display ultrasonic waves in transparent solids by Hall [9] in 1977. Then, Dally [10] reviewed the most common imaging recording methods and put forward the possible applications of dynamic photoelasticity. In the 1980s, Ying et al. [11-15] did a series of investigations on the scattering of ultrasonic waves in solid medium by the dynamic photoelastic visualization. The results not only verified the conclusion of theoretical analyses, but also showed some new phenomena. Recently, this method has been applied to the study of Time-of-Flight Diffraction (TOFD) technique and ultrasonic phased arrays [16-17] to explain the principle of ultrasonic detection methods. Current studies of dynamic photoelastic method are concentrated on the transient problems and ignore the steady-state ultrasonic field. However, steady-state field changes with time periodically, thus some useful information, such as directivity patterns, can be obtained from the photoelastic photograph.

In this paper, the directivity of ultrasonic scattering field is investigated by photoelastic technique. Taking the cylindrical cavity for example, the scattering field of longitudinal waves and the directivity patterns are displayed by dynamic photoelastic method and FEM, respectively. The comparison reflects the advantage of dynamic photoelastic technique in the study of practical scattering field.

2. DYNAMIC PHOTOELASTIC IMAGING SYSTEM

The dynamic photoelastic imaging system employed in this paper is shown schematically in Fig. 1, and this setup is established on an optical table to reduce the disturbance of mechanical vibration. The light source is a pulsed laser, which emits a high intensity green light beam with very short duration (about 3.8ns). Trigger pulses are sent from an interface controller to laser and ultrasonic transmitter for their synchronization with each other. The laser is triggered after a time delay, so we can change the position of ultrasonic waves in sample to record the propagation process of various waves by adjusting the time delay.

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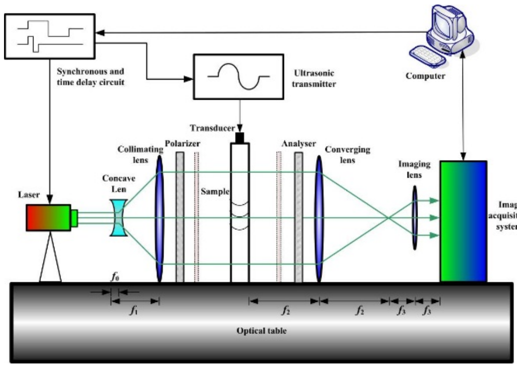


Figure 1. The schematic diagram of photoelastic system

In the optical system, the polarization direction of polarizer and analyzer are orthogonal, and the sample is made of annealed optical glass. The dotted lines between the sample and the polarizer indicate a couple of quarter-wave plates, which make the laser light through the sample turn into circularly polarized light. Based on the theory of two-dimensional photoelasticity, the light intensity *I* emerging from the analyzer can be defined as

$$I = I_0 \sin^2\left[\frac{\pi Cl}{\lambda}(\sigma_1 - \sigma_2)\right] = I_0 \sin^2\left(\frac{2\pi Cl}{\lambda}\tau_{\max}\right), \quad (1)$$

in which I_0 is the light intensity emerging from polarizer, *l* is the length of the stressed model,   is the wavelength of incident light, *C* is the stress-optical constant of sample material, and $_{max}$ is the maximum shear stress. Besides, $_1$ and $_2$ are the principal stresses, which caused by ultrasonic waves are relatively small in the sample, so it can be approximately considered that

$$\sin\left[\frac{\pi Cl}{\lambda}(\sigma_1 - \sigma_2)\right] \approx \frac{\pi Cl}{\lambda}(\sigma_1 - \sigma_2) \cdot \quad (2)$$

From Eq.1 and Eq.2, we can get

$$I \propto (\sigma_1 - \sigma_2)^2 \propto \tau_{\max}^2 \cdot \quad (3)$$

In another hand, the image acquisition system takes the photoelastic photographs, and the original photograph is usually encoded onto RGB (red-green-blue) color channels. The laser source used in the experimental system is green light, so only one color channel is useful in the image analysis. There are 256 gray levels per pixel in the photograph, and the gray level N reflects the quantity of illumination which is proportional to the output light intensity *I*, so it is easy to get that

$$N \propto (\sigma_1 - \sigma_2)^2 \propto \tau_{\max}^2. \quad (4)$$

By using this photoelastic system, the scattering field caused by continuous waves can be displayed, and based on Eq.4, the directivity patterns can be obtained.

3. DYNAMIC PHOTOELASTIC EXPERIMENT

Although the scattering field of plane longitudinal wave by the cylindrical cavity can be calculated by classical theory, the ultrasonic wave radiated by transducer is not an ideal plane wave, due to its geometry and boundary conditions. As a result, the scattering field radiated by a piston-type transducer is studied by photoelastic method in this section.

The transducer employed has a central frequency of 3MHz, and the diameter of the piezoelectric crystal is 16mm. The optical glass sample, whose parameters are listed in Table 1, has a thickness of 30mm, and the length and width are both 120mm. A cylindrical cavity of 2mm bored through the parallel faces is located in the middle of the sample. Sine burst signal is delivered to stimulate the transducer which is put at the left side of the sample.

Table 1. Properties of the sample

Modulus (10^9 *Pa*)	*Density* (10^3 *kg/m*^{3})	*Poisson's ratio*
79.2	2.52	120

Fig.2 shows that the mutual interference between the incident waves and scattered waves comes into being the steady-state ultrasonic field, in which various wavefronts are overlapped. In this photoelastic photograph, the gray level *N* per pixel reflects the energy of maximum shear stress $_{max}$. On one hand, the energy of scattering field focuses on the left mainly for the presence of incident waves; on the other hand, the energy will decrease gradually with the increase of the propagation distance. Owing to the unsaturated gray levels, the directivity patterns of ultrasonic scattering field can be displayed by the photoelastic photograph. By defining the center of cavity as the origin point of polar coordinates and the distance to it as *r*, the relative maximum values in Fig.2 are picked out at a certain *r*. Two directivity patterns are plotted in Fig.3, where *r* equals to 8.29mm and 19.16mm, respectively. The main lobe and side lobes between 120° and 240° reflect the incident waves and various scattered waves backward, respectively; while the side lobes around ±30° stand for the creep waves propagating along the surface of the cavity.

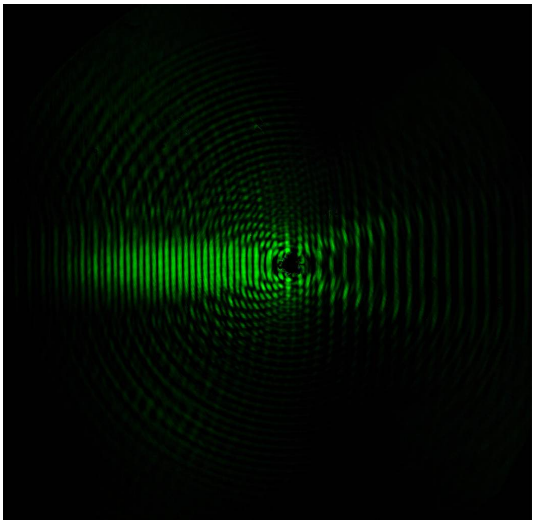
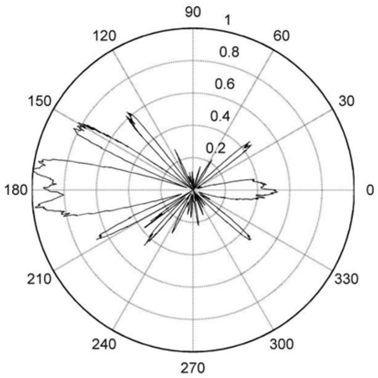
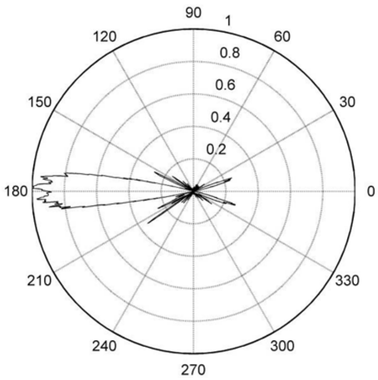


Figure 2. The scattering field of longitudinal waves by a cylindrical cavity



(a). The directivity patterns at r=8.29mm



(b). The directivity patterns at r=19.16mm

Figure 3. The directivity patterns of scattering field

4. NUMERICAL SIMULATION

In order to verify the reliability of the dynamic photoelastic experimental results, FEM is also used to calculate the scattering field by the cylindrical cavity.

In this section, the commercial finite-element package COMSOL Multiphysics is selected to simulate the two-dimensional scattering field. The calculated result is shown in Fig.4, in which the shooting moment is approximately the same as the dynamic photoelastic experiments. In general, the simulated image has a good consistency with the photoelastic photograph in Fig.2 apart from the fringe spacing on the right of the cavity. This is caused by many factors, which contain the shell, the backing and the fabrication technique of transducers, so it is hard to be simulated exactly using software.

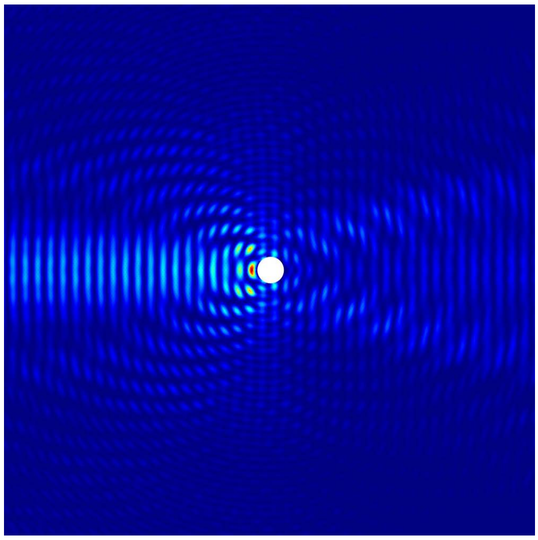


Figure 4. The scattering field simulated by FEM

Based on the simulation result by FEM, the directivity patterns is presented in Fig.5, taking r equals to 8.29mm for example. Compared with Fig.3 (a), it is easy to find that the main differences lie in the main lobe around 0° and the side lobes around ±90°. The latter is determined by the length of stressed model (referring to Eq.1). The FEM model is a two-dimensional model, in which the length l is defaulted as a constant. However, the piezoelectric crystal of transducer is circular, so the length of practical stressed model doesn't have a uniform distribution in the dynamic photoelastic experiment, which leads to parts of the side lobes in Fig.3 much smaller than the simulation result.

Fig.4 presents the ideal scattering field rather than the practical scattering field in solid. The comparison reveals that dynamic photoelastic method not only shows the ultrasonic scattering field and the directivity patterns, but also fully reflects the influence of transducer to the ultrasonic field, which confirms the authenticity and reliability of this experimental method in the study of the directivity.

However, some errors brought by the dynamic photoelastic imaging system will influence the accuracy of experimental results. For examples, the directivity patterns don't have an absolute symmetry which is caused by the instability of laser pulse; the background noise in the photoelastic photographs disturbs the judgment of gray levels; the gray levels are limited to 256 numbers.

5. CONCLUSION

The dynamic photoelastic technique can not only shows the ultrasonic scattering field and the directivity patterns, but also fully reflects the influence of transducer characteristics to the ultrasonic field. According to the experimental results, the following conclusions can be made:

(1). Photoelastic technique has the advantage to study the ultrasonic scattering field near defects in solids.

(2). Quantitative measurement can be achieved based on the gray level of the photographs.

(3). Photoelastic technique is a useful tool to check the theoretical and numerical predictions.

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