SELF-FOCUSBING SURFACE WAVE ARRAY

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INTRODUCTION

Nondestructive testing (NDT) with surface waves is very sensitive to surface defects because the ultrasonic energy is concentrated in a small region at the surface of a specimen. The penetration depth of a surface wave is of the order of a wavelength [1].

Conventional NDT often uses a focused transducer to increase the amplitude of ultrasonic signals. Since focused transducers have a fixed focal point, mechanical movement of the transducer is generally required, resulting in long inspection times and extra expenses for a scanning device. A phased array technique allows one to electronically move the focal point without mechanically moving the transducer itself [2,3].

A technique for self-focusing on a surface defect with a linear array of surface wave transducers is presented in this paper. The technique is applied to automatically focus on a reflector within the steering range. Since beamsteering with a linear array can move the focal point within a 2D-plane, in principle the entire specimen surface can be tested. The self-focusing procedure first measures the backscattered signals of a first transmission generated by a single element. A cross-correlation determines the time-of-flight differences of the backscattered waves, which are then used to adjust the times of excitation of the individual array elements for focused transmission. After iteration of this process, the time delays for excitation of the transducer elements ensure that all signals arrive at the defect at the same time. A focused surface wave now sonifies the defect and next the scattered waves are measured. Using the time differences once again the received signals are aligned and their superposition provides the focused signal. Experimental results prove the ability of the system to self-focus on a defect. For the case that there is more than one defect, the technique has been extended to focus on the defect that produces the largest backscattered signal. Current research targets Lamb wave focusing. Experiments have been successfully performed to focus the first antisymmetrical Lamb mode on artificial defects in an aluminum sheet.
Figure 1. Self-focusing procedure.

Figure 2. Self-focusing system.
In earlier work, Fink et al. [4] showed how to focus surface waves with the technique of the time-reversal mirror. The approach of this paper uses less expensive hardware and an easier algorithm.

SELF-FOCUSING ULTRASONICS

Our self-focusing procedure will automatically adjust the focal point on the reflector producing the biggest signal within the focal range. The steps of the procedure are shown in Figure 1. A center element of the transducer array is excited (Figure 1a) and the defect scatters the incident wave. All transducer array elements collect the backscattered wave (Figure 1b). The arrival time for each element is dependent on the path length between the defect and the individual element. After collecting the backscattered wave with all elements a cross-correlation technique is used to determine the time-of-flight differences. The algorithm for the time-discrete cross-correlation [5] is given by

\[
C_{xy}[m] = \frac{1}{N} \sum_{n=0}^{N-1} X[n] \cdot Y[n+m], \quad m = 0,1,\ldots,N-1.
\]

(1)

The cross-correlation will shift one sequence sample by sample with respect to the other and compare the two signals for each shift. Maximum similarity will result in the maximum value for the cross-correlation and therefore allows the determination of the time-of-flight difference. The time shifts determined by the cross-correlation are the time delays for reception. The element which received the signal last (i.e. has the longest path) has the biggest time delay.

In transmission focusing the waves sent out by all elements arrive at the defect at the same time by reversing the receiving time delays. The element with the longest path is fired first (Figure 1c). Transmission focusing ensures that the sound energy at the defect location is much larger compared to a conventional transducer with the same aperture. After scattering of the focused signal by the defect, reception focusing uses the previously determined receiving time delays to align the signals received by all elements (Figure 1d).

After the alignment, the positive and negative half-waves of the ultrasonic signals will match. A superposition of all shifted signals then leads to constructive interference and produces the focused signal.

SELF-FOCUSING SYSTEM

Phased array systems are often used in the medical field. The cost of these systems prevented a widespread use of electronic focusing of ultrasonic waves in the field of non-destructive testing. The presented system which was developed at Northwestern University provides a low-cost alternative using standard components for the data acquisition and the pulser-receiver units. Also the number of elements is smaller than what is often found in the medical field. A block diagram of the system is given in Figure 2.

An external trigger source synchronizes the system. An arbitrary function generator (Tektronix AFG 5101) periodically generates the master pulse which triggers the data acquisition and provides the input signal for the delay electronics. This master pulse is present at all eight outputs of the delay electronics, but each pulse is delayed by a time specified by the computer.
To provide a wide steering range, time delays from 0 to 8999 nanoseconds can be generated by the delay electronics in increments of 25 nanoseconds. A measurement with an impedance analyzer proved the uniformity of the center frequency for the transducer elements. The size of each element is 3.5 by 8.3 mm which was found to be a good compromise between high ultrasonic energy and useful steering capabilities. The transducer is coupled to the specimen through an acrylic wedge. Snell's Law which relates the wave angles to the wave speeds determines the wedge angle. For an aluminum specimen with a Rayleigh wave speed of 2935 m/s and an acrylic wedge with a longitudinal wave speed of 2700 m/s, the wedge angle for surface wave generation is 67°. Stable coupling and transducer position are ensured by a fixture which clamps the transducer onto the specimen. Mild pressure was necessary to obtain useful signal amplitudes and to maintain the position. The measurements are performed in the pulse-echo mode and the ultrasonic reflections are collected with the transducer array. The receivers amplify the signals by 40 dB and additional high-pass filtering reduces the low-frequency noise. The data acquisition is done with a digital oscilloscope (Tektronix TLS216) which can acquire up to 16 signals at a time. This leaves room for a future upgrade of the system. The data is transferred to the computer via GPIB (General Purpose Interface Bus) to perform reception focusing. The receiving time delays are determined with the cross-correlation and used for alignment of the signals. The superposition of the aligned signals results in the focused signal.

CHARACTERIZATION OF THE SELF-FOCUSBING SYSTEM

The spatial resolution of a phased array system is dependent on the size of the focal point. Direct amplitude measurements in the pulse echo mode will provide information about the width of the ultrasonic beam, but contact transducer testing always incorporates the difficulty of varying transducer coupling. Therefore, a different way was chosen to gain information about the focal point. The transducer array was mounted on a flawless specimen and the focal point was adjusted to a known position. A Sagnac-laser interferometer was used to measure the surface wave displacement across the focal point [6]. A lateral scan and an axial scan were performed.

The lateral scan in Figure 3 shows a narrow peak and the 3dB beamwidth is 1.8 mm. The axial scan has a flatter characteristic, which is due to the fact that the time delays along the focal axis do not change as quickly as they do in the lateral direction. This does not limit the usefulness of the system, because the time-of-flight information of the ultrasonic signals allows us to determine the axial distance between array and defect.

![Lateral Scan](image1)

![Axial Scan](image2)

Figure 3. Displacement measurements across the focal point.
Figure 4. Self-focusing of Rayleigh waves for off-axis defect.

Figure 5. Self-focusing on reflector which produces the largest reflection.
Various experiments with one or two defects within the focal range were carried out with the self-focusing surface wave array. The distances between defect and transducer array vary between 5cm and 15cm. The defects are holes in a thick (with respect to the wavelength) aluminum plate with diameters from 0.8 mm to 2 mm. First the case of a single reflector within the focal range is discussed. The signals for an off-axis defect are presented in Figure 4.

First the unfocused system is shown. All transducer elements are excited at the same time. These waves hit the defect at different times and result in multiple reflections in the ultrasonic signals. A superposition results in a noisy signal without any information about the defect. Following the self-focusing procedure, significant amplitude amplification can be achieved. After the initial insonification with the center element, the time-of-flight differences are determined with the cross-correlation and used for transmission focusing.

Reception focusing is performed and it can be clearly seen that the signals are perfectly aligned, i.e. positive and negative lobes match and ensure maximum amplitudes for the superposition. The superposition of the shifted signals is the focused signal.

For the case of multiple defects within the focal range, the self-focusing procedure has to be iterated to focus on the defect within the focal range which produces the biggest reflection. Two holes of different diameters are drilled into the specimen as seen in Figure 5. During the first iteration, the time delays for the elements close to the small defect are incorrect. Larger signals return from the smaller reflector and the cross-correlation will not give the correct delays for focusing on the largest reflector. Each iteration though will increase the energy focused on the larger reflector and after four iterations all delays are adjusted for focusing on the larger reflector. Figure 5 presents the iteration process.

For the first time, electronic focusing of Lamb waves has been performed. Experiments with the first antisymmetrical (a$_{1}$) mode in an aluminum sheet with artificial defects showed the potential of self- focusing for guided waves. The a$_{1}$-mode was the fastest mode for the given product of frequency and thickness and was also fairly nondispersive. Experimental results for the on-axis case are shown here. A crack was approximated with an EDM-wire cut of 0.1mm width which was insonified head-on. The results are shown in Figure 6.

The signals for the unfocused system show high low-frequency noise and small ultrasonic reflections. Self-focusing on the crack tip again results in a large focused signal with a clean waveform.
Figure 6. Self-focusing of Lamb waves for on-axis crack.
CONCLUSION

Self-focusing of Rayleigh and Lamb waves with a low-cost phased array system has been presented. A nondestructive inspection can be carried out without mechanical movement of the transducer and significant amplitude amplification can be achieved.

Further investigation of other Lamb modes will follow. Testing of specimens of complex shape is possible, because the self-focusing algorithm will also work for curved surfaces, and therefore can be used in a wide range of NDT-applications.

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REFERENCES