Noncontact continuous wavefront/diffractive acoustic elements for Rayleigh wave control

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(Received 5 February 1999; accepted for publication 21 March 1999)

A laser is used to excite Rayleigh waves on a sample. The optical distribution of the laser energy as it strikes the sample is controlled using a computer generated hologram—this optical distribution determines the initial acoustic wavefront and hence the acoustic amplitude distribution. In this letter, we present two designs of acoustic elements which use diffraction of the Rayleigh waves as a means of controlling the acoustic amplitude distribution. *© 1999 American Institute of Physics.* [S0003-6951(99)02824-7]

Laser ultrasonics has many well-documented advantages over traditional transducer-based techniques;[1] however, one of its major limitations is that of optical detector sensitivity. This problem has lead to the development of ways of controlling the distribution of the excitation laser source on the sample surface, so that detectable power levels can be generated without damaging the sample. Computer generated holograms[2] (CGHs) are an effective means of producing any desirable intensity distribution of laser energy on a sample surface, giving control over the initial acoustic wavefront. Multiple-line profiles have been used to control the frequencies of Rayleigh waves that are generated.[3] Arc profiles have been used in fluid-coupled systems to focus Rayleigh waves,[4] and indeed focusing occurs naturally on the scanning acoustic wave microscope[5] because the leaky Rayleigh waves are excited on a ring. More recently, we have used arc profiles in a noncontact system using CGHs.[6,7] In this letter, we present two designs of acoustic elements which use *acoustic wave diffraction* as a means of controlling the amplitude distribution. The eventual impetus behind this research is to control the acoustic focus position in an adaptive acoustic system.[7]

At this point it is useful to draw analogies between the acoustic elements described below and some common optical elements. A simple optical convex lens is described as a refractive element because it uses refraction to, for example, focus a collimated beam of light to a point. The ''arc'' acoustic element described by Liu *et al.*[6] generates a continuous acoustic wavefront which is focused to a point, so the device may be thought of as analogous to a refractive lens, even though there is no acoustic refraction occurring.

A zone plate or diffractive optical element may also be used to focus a collimated beam of light. Using the analogy between optical and acoustic elements, one can imagine that there is an equivalent of an optical zone plate in the acoustic domain. This would consist of discrete segments or zones, rather than a continuous line or curve. Drawing from these analogies between optical and acoustic elements, a device that produces a continuous wavefront would be termed a continuous wavefront acoustic element, while a device that produces a set of discrete wavefronts would be termed a diffractive acoustic element.

Both the simulated (predicted) and measured Rayleigh wave amplitude distributions, or *point spread functions* (psfs) produced by the elements are presented.

The Rayleigh waves are generated by a mode-locked, *Q*-switched Nd:YAG laser, with an average power output of 2 W. The *Q*-switch triggers an envelope of approximately 30 short mode locked pulses, each pulse separated from its neighbor by ≈ 12 ns. The time period between every *Q*-switch burst is one millisecond. The pulses have a fundamental frequency of 82 MHz, with harmonics extending into the gigahertz region. The excitation laser energy is projected onto the sample surface with the binary phase CGH.

The Rayleigh waves are detected point by point using a specialized knife-edge detector. The detection point is mechanically scanned relative to the excitation source and the sample. Fast analogue electronics[8] are used to capture the peak amplitude of the envelope at each point. The sample used is optically smooth.

The first element consists of a line of 75 displaced segments, the separation between the front and back segments being equal to half the Rayleigh wave wavelength at the

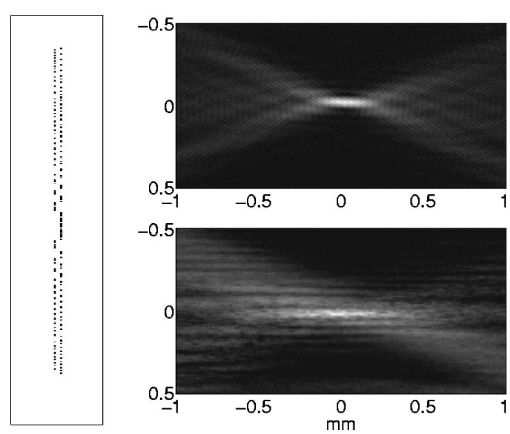

FIG. 1. Diffractive acoustic element (expanded horizontal scale), predicted (top) and measured (bottom) psfs.

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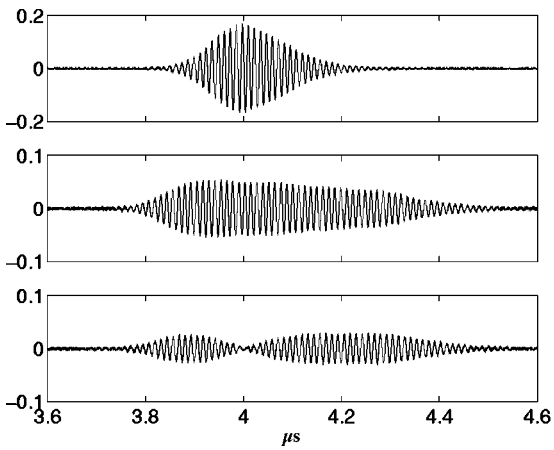

FIG. 2. First trace was obtained from the focus of an arc acoustic element and shows no envelope broadening. The second trace was obtained from the focus of the diffractive element shown in Fig. 1. The third trace was obtained from just above the focus of the diffractive element, within a ''dark lobe.'' The horizontal scale denotes time in μs since Rayleigh wave excitation.

fundamental frequency of 82 MHz. As with optical zone plates,[9] the element produces a converging and a diverging beam corresponding to the $+1$ and -1 orders.

Figure 1 shows the element itself, along with the predicted and measured psfs of the focus of the converging beam. The focus of the measured psf is less well defined than the predicted psf. This is not due to any failings of the acoustic element, rather it is due to the finite envelope length of the source and hence of the Rayleigh wave packet. The path length difference for acoustic waves generated at the center and edge of the acoustic element is 1.4 mm. At a Rayleigh wave velocity of $\approx 3100\,\mathrm{ms}^{-1}$, this equates to a time delay of $\approx 450\,\mathrm{ns}$, or 37 cycles at 82 MHz: the temporal length of the acoustic envelope at the predicted focus is more than doubled, see Fig. 2. Since the measured psf in Fig. 1 is simply, a measure of the *peak* of the pulse envelope at each point, the focus appears to be less well defined.

The temporal spreading of the resulting pulse envelope around the focus, in addition to reducing the peak amplitude, also reduces the amount of destructive interference taking place between wavefronts originating from different zones. It is this destructive interference that leads to the characteristic dark lobes above and below the focus in the simulated psf in Fig. 1. Since the Rayleigh wave packets are separated temporally (although not spatially), they do not interfere, as shown in the third trace of Fig. 2. This leads to a larger psf.

To allow the pulse envelopes originating from different zones to interfere, the length of the generated pulse envelopes would have to be increased. Since this is not possible with our experimental setup, the equivalent is achieved by

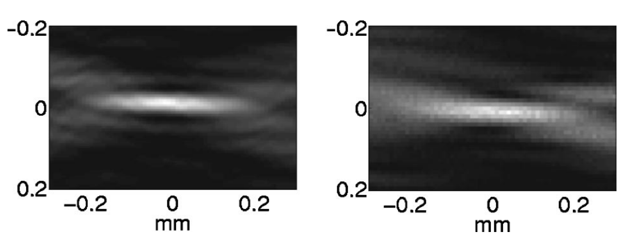

FIG. 3. Predicted (left) and 82 MHz filtered measured (right) psfs at focus.

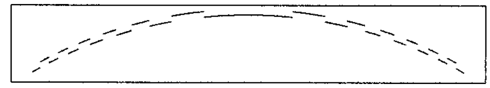

FIG. 4. Hybrid continuous wavefront/diffractive acoustic element. The spacing between front and back segments has been exaggerated.

acquiring the full waveform at each scanning point, and taking the 82 MHz component of the Fourier transform of the signal, effectively increasing the pulse envelope length by very sharp filtering. The results are shown in Fig. 3. Since the whole waveform must be captured at each point in order to obtain the 82 MHz component, rather than just the peak amplitude, scanning takes much longer, hence the small scan area.

To address the problems of the acoustic element above, while still retaining aspects of diffraction to control the position of the Rayleigh wave focus, a hybrid continuous wavefront/diffractive acoustic element has been developed, see Fig. 4. This element has aspects of both a regular arc and the zone plate described above.

The arc is broken into just 13 zones. The arc provides the dominant focusing effect. Due to the reduced number of zones, the maximum delay of wavefronts originating from the extremes of the element compared to wavefronts from the center of the element is greatly reduced to six cycles, allowing effective interference—and therefore focusing—to take place. The relatively weak zone plate moves the focus to a different position.

To demonstrate that the theory works, psfs were acquired both by simulation and experimentally at two ultrasonic frequencies, 82 and 164 MHz, see Fig. 5. This hybrid element is designed for 82 MHz. The zone spacing is equal to a whole wavelength at 164 MHz, thus the zone plate does not perturb the 164 MHz Rayleigh waves. These waves are focused according to the arc radius, whereas the 82 MHz

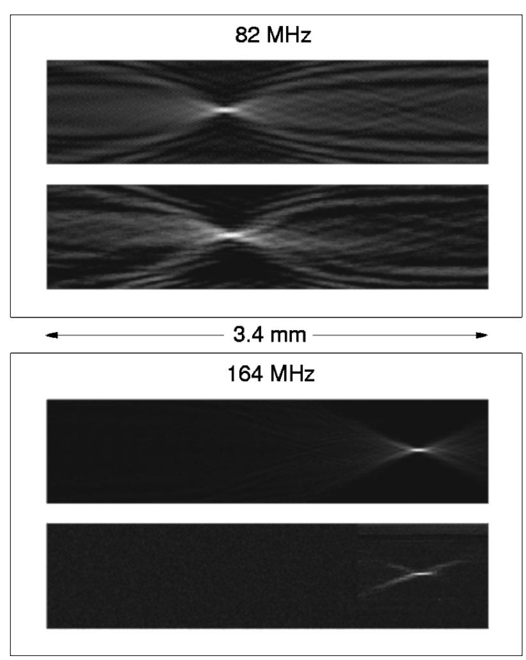

FIG. 5. PSFs of the hybrid acoustic element. In the upper box are the predicted (first) and measured (second) psfs at 82 MHz. In the lower box are the predicted and measured psfs at 164 MHz.

Rayleigh waves are focused according to the combined focusing powers of the arc and the zone plate.

This letter has shown that diffractive acoustic elements may be used to produce focused Rayleigh wave amplitude distributions. Problems with finite pulse envelopes have been addressed by using a hybrid continuous wavefront/diffractive acoustic element. Measured amplitude distributions show excellent agreement with design simulations.

The authors wish to acknowledge the Engineering and Physical Sciences Research Council (EPSRC) and Rolls Royce PLC who have supported this work. They would also like to thank Glasgow University for fabrication of the CGHs.

[1] C. B. Scruby and L. E. Drain, *Laser Ultrasonics, Techniques and Applications* (Adam Hilger, Bristol, UK, 1990).
[2] M. Clark and R. Smith, Opt. Commun. **124**, 150 (1996).
[3] M. Clark, F. Linnane, S. D. Sharples, and M. G. Somekh, Appl. Phys. Lett. **72**, 1963 (1998).
[4] H. Koymen, A. Atalar, T. Ciloglu, M. Onder, C. Uzel, and H. Yavuz, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **34**, 399 (1987).
[5] I. R. Smith, H. K. Wickramasinghe, G. W. Farnell, and C. K. Jen, Appl. Phys. Lett. **42**, 411 (1983).
[6] M. Liu, H. P. Ho, M. G. Somekh, and J. M. R. Weaver, Electron. Lett. **31**, 264 (1995).
[7] M. Clark, S. D. Sharples, and M. G. Somekh, *1998 IEEE Ultrasonics Symposium*, IEEE and UFFC (IEEE, Piscataway, NJ, 1998).
[8] M. Clark, S. D. Sharples, M. G. Somekh, and A. S. Leitch, Electron. Lett. **35**, 346 (1999).
[9] E. Hecht, *Optics* (Addison–Wesley, Reading, MA, 1998).