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Selective excitation of single-mode acoustic waves by phase velocity scanning of a laser beam

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A novel method for selective generation of single-mode acoustic waves in multimode media has been developed using a laser beam scanned at the phase velocity of a specified mode. In dispersive media, the acoustic frequency can be varied by changing the scanning velocity. The number of carriers in the generated wave packet is proportional to the difference between the phase and the group velocities. These features were experimentally verified in the fundamental symmetric and asymmetric Lamb waves on an aluminum plate generated by a long-pulse Nd:YAG laser. Applications to anisotropy and thickness measurements are discussed.

Many modes of acoustic waves can be propagated along a solid structure. For example, symmetric and asymmetric modes[1] are propagated along plates, and torsional, flexural,[2] and longitudinal modes[3] along rods, clad rods, and fibers. They are characterized by the velocity dispersion curve, or the relation between the phase or group velocity and the frequency of the acoustic waves. They are useful for the quantitative nondestructive evaluation (QNDE) of defects and thickness of plates and rods. Nevertheless, if there are different modes at the same frequency, they tend to overlap each other and distort the wave form. This distortion is detrimental for precise measurements.

In this letter we present a novel method to solve this problem by a selective generation of single-mode acoustic waves in multimode media. This method is based on the generation of sound by scanning a laser beam along the surface of water[4,5] or of a solid.[6] In previous works, however, distinction between the phase and group velocity was not made clear. The essential procedure of the present method is to vary the scanning velocity of the beam so as to adjust it to the phase velocity of a specified mode in dispersive media. The first experimental verification of this phase velocity scanning (PVS) method is presented using a long pulse (ms) YAG laser to generate MHz Lamb waves on an aluminum plate. A simple equation to predict the performance of this method is also shown.

The experimental setup is illustrated in Fig. 1. A flash lamp pumped Nd:YAG laser beam (pulse width = 2 ms, pulse energy = 1 J, divergent angle = 10 mrad) was deflected using a polygon mirror scanner with maximum rotation speed of 24 000 rpm. The beam was focused by a cylindrical lens with focal length of 600 mm into a rectangular spot of length 10 mm and width 1–2 mm on a 1.5-mm-thick aluminum plate. The scanning speed V of the spot was varied by changing the rotation speed of the mirror. Total scanning length L of the beam was 50 mm. The acoustic wave was detected using a piezoelectric transducer (Panametrics A534S) with a surface wave wedge located 10 mm away from the scanning area on the sample. The center frequency of the transducer was 2.23 MHz and 6 dB bandwidth was 1.18 MHz. A digitizing oscilloscope was triggered by an optical signal detected by a photodiode (PD) placed aside the lens and the wave form was recorded.

Digitized wave forms for the scanning velocities between 3164 and 2730 m/s are shown in Fig. 2. Clear oscillation was observed without any averaging and signal processing. The number of carriers and the frequency of the oscillation was different for different scanning velocities. The frequency spectrum of the oscillation was obtained by Fast Fourier Transform analysis. A power spectrum with a single peak was obtained from any wave forms in the scanning range between 3164 and 2960 m/s and between 2900 and 2720 m/s. The product of the peak frequency F of the power spectrum and the plate thickness D (1.5 mm) is plotted as closed circles in Fig. 3 as a function of the scanning velocity V along the left vertical axis.

Solid curves in Fig. 3 are calculated phase velocity v_P of the fundamental symmetric S_0 and asymmetric A_0 Lamb wave[1] on an aluminum plate as a function of the FD value along the horizontal axis. The material constants used are $c_{11} = 1.113\times10^{11}$ N/m^2, $c_{44} = 0.261\times10^{11}$ N/m^2, and density $= 2.699\times10^3$ kg/m^3. The calculated group velocities v_G are also plotted for comparison. It is clearly seen that the experimentally obtained values of the product FD agreed with the calculated phase velocity dispersion curves. The agreement is remarkable in the S_0 mode. Sys-

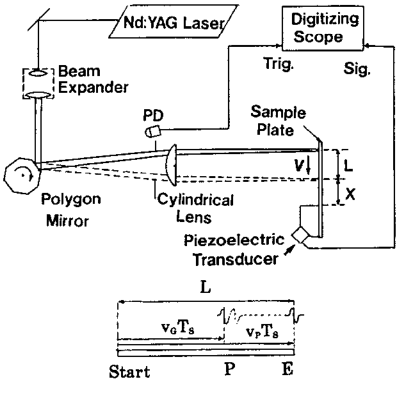

FIG. 1. Experimental setup for the generation of dispersive Lamb waves on a plate by scanning a YAG laser beam.

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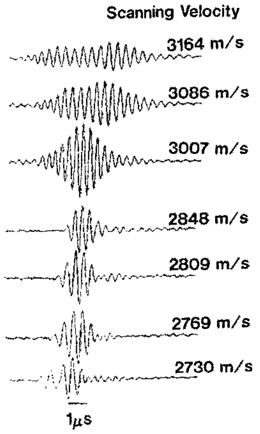

FIG. 2. Detected wave forms of the Lamb waves on 1.5-mm-thick aluminum plate with different scanning velocity.

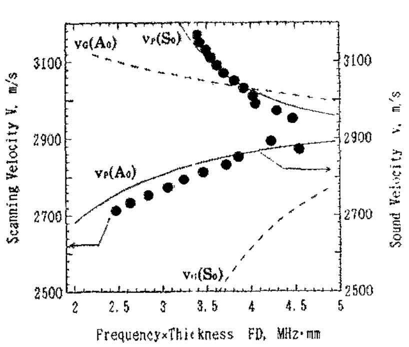

FIG. 3. Relation between the frequency F of generated Lamb waves multiplied by the plate thickness D and the laser scanning velocity V (closed circles). Solid curves are calculated phase velocities of the fundamental symmetric (S_0) and asymmetric (A_0) Lamb wave. Broken curves are calculated group velocities of the two modes.

tematic shifting in the A_0 mode is probably due to the limited bandwidth of the transducer, because the observed frequency shift was towards the center frequency of the transducer. Thus it was verified that the proposed phase velocity scanning (PVS) is an effective procedure for generating single-mode Lamb waves.

The mode selectivity of the PVS method is now compared with conventional methods for generating Lamb waves, where alternating forces with a given frequency F are applied to the plate. In the range of Fig. 3, the force will generate two wave packets of the S_0 and A_0 mode. They cannot be separated until propagating for a period of $Tv_{GA}/(v_{GA}-v_{GS})$, where T is the duration of the wave packets and v_{GS} and v_{GA} are group velocities. Supposing that $T = 10$ μs, $v_{GA}=3000$ m/s, and $v_{GS}=2700$ m/s, which are reasonable assumptions at $D=1.5$ mm and $F=3$ MHz, this period is 100 μs. This means that the plate should be longer than 300 mm, rather a strong restriction. The PVS method, in contrast, specifies the phase velocity v_P first, rather than the frequency F. It is then possible to establish a single mode just after the scanning length L. Although the difference between the phase velocities of S_0 and A_0 mode is less than 100 m/s at FD = 4.5 MHz mm, the two modes were selectively generated. Since $L = 50$ mm, it is an improvement by a factor of 6 over the necessary length of 300 mm in the conventional method.

In media with multiple modes of the same phase velocities, it is necessary to select a single mode by frequency filtering the observed wave form. Therefore, the sharpness Q of the peak in the power spectrum, or equivalently, the number of carriers N in the observed wave packets, are important parameters. We derived a simple equation to predict N in terms of the scanning length L and frequency F. Suppose that the laser beam starts from the left and arrives at the end point E after the scanning period T_S in the inset of Fig. 1. The energy of the strain generated at the starting point propagates a distance $v_G T_S$ and arrives at point P. Therefore, between the point P and E there is a wave packet with the length of $[v_P - v_G]\ T_S$, where [ ] denotes the absolute value. Then the number of carriers is

$$N=[v_P-v_G]T_S/\lambda, \tag{1}$$

where λ is the wavelength. Considering that $T_S = L/v_P$ and $\lambda = v_P/F$, we obtain

$$N=FL[v_P-v_G]/v_P^2. \tag{2}$$

This equation indicates that the number of carriers N is proportional to the difference between the phase and the group velocities.

The value of N was evaluated using calculated velocities in Fig. 3 and values of F obtained from the power spectrum of wave forms in Fig. 2. The results are listed in Table I as N(cal). For comparison, the number of carriers N crossing the threshold V_t of each waveform in Fig. 2 was counted. Then the number of reverberation N_r caused by the transducer characteristics was estimated using a block of aluminum without dispersion ($v_P=v_G$). It was estimated to be $N_r=2$, and subtracted from the count N. The resultant N(obs) is listed in Table I. Here, V_t was set to 20% or 30% of the maximum amplitude, giving the identical results. It is known that N(cal) of the S_0 mode decreases as v_P decreases, N(cal) of the A_0 mode is significantly smaller than that of S_0 mode, and slightly increases as v_P decreases. This trend was also observed in the N(obs). The sharpness Q of the peak in power spectrum was also evaluated as the ratio of the peak frequency over the full width at half maximum (FWHM). It is also listed in Table I. Again, the overall trend of Q agreed with that of N(cal), although the absolute value varied depending upon the definition of the width of the peak.

TABLE I. Calculated and observed number of carriers N(cal) and N(obs) of generated Lamb wave packet with several phase velocities v_P. The sharpness Q of the peak in the power spectrum is also listed.

v_P (m/s)	3164	3086	3007	2848	2809	2769	2730
Mode	S_0	S_0	S_0	A_0	A_0	A_0	A_0
N(cal)	9.0	7.5	5.4	2.9	3.3	3.7	3.9
N(obs)	12–13	10	7	2	2	2	3
Q	12.9	10.8	10.2	4.1	3.9	4.7	4.2

From the above comparison, Eq. (2) was verified semiquantitatively. To perform more precise comparison, transducers with flat frequency response or a calibration procedure of the transducer characteristics should be employed. Furthermore, the width of the wave packet and number of carriers N should increase during propagating to the transducer due to the group velocity dispersion. This effect would explain the difference between N(obs) and N(cal) of the S_0 mode with large dispersion.

Finally, we discuss the advantages of the PVS method over the existing laser generation methods in terms of the laser requirements and the directionality. If one uses modulated continuous lasers or pulsed lasers,[7] the frequency of the generated acoustic waves is restricted by the modulation frequency or pulse width of the laser. The important advantage of the PVS method is that the relatively inexpensive long pulse lasers (ms) or continuous lasers can be used to generate MHz or higher frequency acoustic waves. The highest frequency $F_{\max}$ is determined by the wavelength comparable to the width of the focused laser beam. Although $F_{\max}$ is 3.1 MHz in the present experiment, it could be increased by using a laser with a smaller divergent angle, shorter focal length lenses, and faster laser deflectors. Another advantage is that we can use low peak power lasers so that the radiation damage is negligible.

Surface acoustic waves generated by a pulsed laser beam in existing methods propagate in at least two opposite directions. In the case of a small object with reflecting boundaries, there will be a problem of unwanted multiple echoes. In the PVS method, this problem is minimized because the propagation of generated waves is restricted to only one direction. The directional waves are particularly useful for in-plane anisotropy measurements and detection of surface discontinuities.[8] Although such waves can be generated also by an optical phased array using fibers,[9] it is necessary to modify the spacing of fibers to vary the wavelength of the acoustic waves. In contrast, the wavelength is automatically varied by changing the scanning velocity in the PVS method.

In conclusion, we have shown for the first time that single-mode acoustic waves are generated in multi-mode media by the phase velocity scanning of a laser beam. Narrow-band waves with a single frequency are generated in dispersive media. The frequency can be precisely measured by the spectrum analysis of detected wave forms and is related to size parameters if the sound velocity is known. Since the apparatus and signal processing of this measurement is simple and reliable, we believe that a practical remote QNDE system could be developed using the PVS method together with noncontacting detectors.[10] Suitable objects are plates, sheets, rods and wires made of metal, ceramics, and polymers. The objects can be moving, in vacuum, or at high temperature, such as in the process of hot rolling, sintering, drawing, and coating.

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