Strongly localized acoustic surface waves propagating along a V-groove

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Strongly localized acoustic surface waves propagating along an immersed V-groove are numerically analyzed and experimentally demonstrated. We analyze the dispersion relation and the distribution of displacements of such groove waves using the compact two-dimensional finite-difference time-domain method. It is shown that they are dispersionless and strongly confined in the lateral cross section. The variations in their velocities as a function of the apex angle are also presented. Furthermore, we implement experimental observation by the near-field detection of these predicted waves in the 30° polymethyl methacrylate groove. The experimental measurements of the wave velocities agree very well with the numerical results. © 2009 American Institute of Physics.

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Acoustic surface waves have been widely utilized in geophysics, underwater acoustics, and nondestructive evaluation as well as acoustic devices. In the propagation process of acoustic surface waves, lateral spreading of the beam induces certain limitations in their applications, which include large distance between neighboring beams and unacceptable level of the sharp bend loss. Thus, various types of waveguides for acoustic surface waves have been proposed to overcome these limitations. Among these waveguides, topographic waveguides (the rectangular ridge and the wedge) have been extensively investigated experimentally and theoretically because of their major features: absence of dispersion, low wave velocity, and strong localization. Recently, the surface plasmon polaritons guided by a V-groove cut into metal [channel plasmon polariton (CPP)] have attracted a great deal of attention. They exhibit subwavelength lateral confinement, relatively low propagation loss, and efficient transmission around sharp bends, which make CPP modes suitable for applications in miniaturization of photonic circuits. Here the geometry of the CPP waveguide motivates our research on acoustic waveguides with analogous geometry for guiding acoustic surface waves. We will show that the immersed V-groove is a type of topographic waveguides for acoustic surface waves, which demonstrates major features for dispersionless waveguide, subwavelength guiding, and low wave velocity, just the same as the other topographic waveguides. However, the immersed V-groove confines almost all the elastic energy in the fluid domain along the bottom of the groove in contrast to the other topographic waveguides, which confine elastic energy in the solid domain of the wedge tips. Therefore, the acoustic groove modes are attractive for possible applications in underwater acoustics, acoustic actuators, and acoustic biosensor.

The analyzed structure is a V-groove cut into a thick polymethyl methacrylate PMMA (\(\rho=1180\) kg/m\(^3\), \(c_L=2500\) m/s, and \(c_I=1400\) m/s) slab, immersed in water; \(\theta\) and \(D\) are the apex angle and the depth of the groove (Fig. 1). Here we fix the depth \(D\) to a certain finite value of 1.5\(a\) [here \(a\) is the quantity used in normalized frequency and equal to 100 times the size of the spatial cell in the finite-difference time-domain method (FDTD) simulation] for the convenience of comparing the numerical results with the experimental measurements, whereas we change the apex angle \(\theta\) to study the velocities of the groove modes as a function of it.

Our numerical analysis is performed by using the compact two-dimensional FDTD, which can provide the dispersion relation and the distribution of displacements of these groove waves. Figure 2 shows the dispersion relation for the groove with apex angle \(\theta=30^\circ\). There are two dispersion lines in the figure, which correspond to the fundamental and the second groove modes. Both modes lie outside, although the second mode is very close to, the dispersion line of Stoneley waves on a flat surface and possess no dispersion. They represent guided modes propagating along the groove. The distribution of displacements of the fundamental mode is plotted in the inset of Fig. 2. It can be seen that the field is concentrated in the liquid domain near the tip and decays up the groove as expected. The lateral cross section of the groove mode is less than a wavelength wide, therefore subwavelength guiding is accomplished. Note that, the dispersion lines of the groove modes deviate from linear relationship and exhibit cutoff at the long wavelength range. This is because, for the truncated grooves, the fields of the groove modes are pushed out of the groove and hybridized with the modes propagating along the edge at both sides of the groove as the wavelength grows. The distribution of displacements of the fundamental mode close to cutoff is also presented in

FIG. 1. Schematic of the V-groove with finite depth \(D\) cut into a thick PMMA slab.

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the inset of Fig. 2. It can be seen that the hybridization does take place. The similar phenomenon has been discussed in Ref. 15 for CPP in truncated groove. We expect that the deviation and the cutoff of the groove modes will disappear if the groove has not been truncated. In addition, the dispersion relation and the distribution of displacements of the groove with apex angle $\theta=30^\circ$ is presented also in Fig. 2. Its dispersion line coincides with that of Stoneley waves on a flat surface, which indicates that this mode will leak into the Stoneley modes on the two horizontal surfaces and depart from the groove, as can be seen in the inset. Below, we will show that the velocities of these groove modes increase monotonously and reach the velocity of Stoneley waves with the increasing apex angle of the groove. Therefore, we conclude that the critical angle for the V-groove considered in this study is $\theta=90^\circ$.

It has been mentioned in Ref. 9 that the mode number and the wave vector of CPP decrease with the increasing apex angle of the groove. Here, we show that there is a similar dependence on the apex angle in the case of our acoustic groove modes. It is easy to obtain the velocities of these modes since the acoustic groove modes are dispersionless, as already noted above. Figure 3 presents the dependence of the velocities of the groove modes as a function of the apex angle. It can be seen that there are two modes in the small apex angle range and the velocities of these mode increase with increasing the apex angle. The velocity of Stoneley waves is the upper limit of the velocities of these modes. Above this limit, these modes will leak into the Stoneley modes on the flat surface and no longer guided by the groove, which has been demonstrated above. The fundamental and the second modes reach the limit at different angles and thus only the fundamental mode exists for the apex angle. Here, we show that there is a small apex angle range and the velocities of these mode in-crease with increasing the apex angle. The velocity of Stoneley waves is the upper limit of the velocities of these modes. Above this limit, these modes will leak into the Stoneley modes on the flat surface and no longer guided by the groove, which has been demonstrated above. The fundamental and the second modes reach the limit at different angles and thus only the fundamental mode exists for the apex angles between $35^\circ$ and $90^\circ$. Note that we find that single-mode guiding can be obtained simply by decreasing the depth of the groove within the angle range of multimode guiding, just as that discussed in Ref. 9, which is not shown here.

For our experiments on observation of the acoustic groove waves, a 60 mm long groove has been carved in a 13 mm thick PMMA slab. The width and the depth were measured as $W=1.1$ mm and $D=2.1$ mm. So, the apex angle was evaluated to be $\theta=30^\circ$. The photograph of the experimental sample is illustrated in Fig. 4(a). It is seen that the groove walls are rather rough. These imperfections will be employed to manifest the track of radiation propagating along the groove, for a portion of the guided mode has been scattered out of the groove by them. Our experimental setup is based on the well-known ultrasonic transmission technique. Two pinducers were employed as ultrasonic generator and receiver, and the sample was placed between them. The entire assembly was immersed in a large water tank. A pulser/receiver generator (Panametrics model 5800PR) produces a short duration pulse. The groove modes were generated by means of the end-fire excitation using ultrasonic waves.

FIG. 2. (Color online) Dispersion relation for various acoustic modes in the groove with depth of $1.5a$. The quantity $V$ is the longitudinal wave velocity of water. Grey solid line: the water line. Red solid line: the dispersion line of Stoneley waves on a flat surface. Blue dotted lines: the fundamental and the second acoustic groove modes for the groove with apex angle $\theta=30^\circ$. Red points: the groove mode for the groove with apex angle $\theta=90^\circ$. Lower insets: distribution of displacements of the fundamental modes for the groove with apex angle $\theta=30^\circ$ at different frequencies, respectively. Upper inset: distribution of displacements of the groove mode for the groove with apex angle $\theta=90^\circ$.

FIG. 3. (Color online) Variations in the velocities of the groove modes as a function of the apex angle of the groove. Red dashed line: velocity of Stoneley waves on a flat surface.

FIG. 4. (Color online) (a) Photograph of the experimental sample. (b) The near-field amplitude distribution of pressure field of the fundamental mode propagating along the groove. (c) The near-field amplitude distribution of pressure field of the Stoneley waves on a smooth surface without groove. (d) The near-field amplitude distribution of pressure field of the fundamental mode in the lateral cross section. Dashed line: the boundary of the groove. The scale unit of length is millimeter in (b)–(d).
beam obliquely incident onto the groove. A metal screen was used to suppress scattered waves in and above the groove, which would interfere the observation. The experimental sample can support two groove modes according to the results presented in Fig. 3. We detected the signal propagating along the groove by a pinducer, and then transformed them into the frequency domain using the fast-Fourier-transformed technique. There are two peaks in the spectrum indeed, which correspond to the two groove modes. The velocities of these modes were measured to be 913 and 1070 m/s, and the numerical results are 896 and 1067 m/s; the agreement is very good. Apart from measuring the velocities of the groove modes, we have also implemented the near-field scanning to demonstrate the near-field amplitude distribution of the pressure field of them. A pinducer with a diameter of 1.5 mm was mounted on a two-dimensional translation stage and brought to a constant distance from the surface of the sample to detect the near-field amplitude distribution of pressure field. The near-field amplitude distribution of the fundamental mode is demonstrated in Fig. 4(b). It can be seen that the acoustic surface waves are indeed guided by the groove, and confined in a finite lateral cross section. We cannot place the pinducer into the groove to measure the amplitude of the groove mode along the bottom of the groove, and then evaluate the propagation distance quantitatively because of the lager diameter of the pinducer. However, the track of the groove mode was clearly distinguishable for distances of ~60 mm, which are about 20 wavelengths long. The near-field amplitude distribution of pressure field of Stoneley waves on a smooth surface without groove is demonstrated in Fig. 4(c) for comparison. The Stoneley waves spread and the finite lateral cross section guiding is achieved. In addition, we show in Fig. 4(d) the near-field amplitude distribution of pressure field of the groove mode when scanning the lateral cross section at the end side of the groove. A lateral V-shaped localization of the amplitude distribution can be seen, although this amplitude distribution is somewhat larger than the cross section of the groove. This can be explained by the insufficient resolution of the pinducer and the diffraction of the out coming signal.

In summary, we have numerically analyzed and experimentally observed strongly localized acoustic surface waves propagating along an immersed V-groove. The dispersion relation and the distribution of displacements as well as the velocities of such acoustic groove waves are analyzed, and then the critical apex angle of the V-groove is determined. In addition, strong localization and reasonable propagation distances of the groove waves have been demonstrated. The measurements of the velocities of the groove waves in the 30° groove agree very well with the numerical results. We expect that the superior features of the acoustic groove waves will further open potential applications for underwater acoustics, acoustic actuators, and acoustic biosensor.

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