Received 11 December 1968

Experimental Detection of Evanescent Ultrasonic Waves by Bragg Diffraction of Light

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The presence of evanescent ultrasonic waves diffracted from an acoustic grating has been detected using Bragg diffraction of laser light. The diffraction of light by these evanescent waves (whose concept stems originally from theoretical arguments) confirms their physical existence. The grating used was designed to diffract the sound into two kinds of wave components: (1) a single propagating wave component moving directly away from the grating; and (2) a pair of oppositely directed evanescent-wave components traveling along the back surface of the grating and forming a standing evanescent wave with exponential decay perpendicular to the grating. Such evanescent waves have shorter wavelengths than propagating waves and hence are inherently capable of better resolution if used for imaging. With the proper orientation of the laser beam with respect to the grating, theory predicts that the above wave components will produce diffracted spots of light symmetrically placed about a central axis. The spots due to the evanescent-wave components are found on an axis perpendicular to that of the spots due to the propagating-wave component, and the evanescent-wave spots are further away from the center. Detection and measurement of the positions and the relative intensities of the spots gives information about the wavelengths of the components and about the rate of exponential decay of the evanescent wave.

The concept of evanescent waves comes originally from theoretical arguments.[1] Scalar-wave theory shows that an illuminated diffracting screen can generate so-called evanescent- or "creeping"- wave components, which travel along the screen's back surface. As these components move away from the aperture, they cling to the screen and transport no energy in the direction perpendicular to the screen. Their amplitudes attenuate exponentially in that direction. Wavelengths are shorter for the diffracted evanescent-wave components than for propagating-wave components. Hence, these waves inherently have better resolution capability for possible use in visual imaging through Bragg diffraction.

To illustrate the principles of evanescent-wave generation, consider the angular spectrum of waves emerging from a long slit in an acoustic diffracting screen irradiated from behind with a normally incident, planar sound beam. The screen and a set of axes are shown in Fig. 1. As illustrated, the screen occupies the $z=0$ plane. The incident radiation travels in the plus z direction. Let the angular spectrum of the diffracted waves be represented by the complex function $U'(f_x)$, where f_x is the x-directed spatial frequency in cycles per unit length. The value of f_x for any plane-wave component is given by the x-axis direction cosine for that component divided by the wavelength λ of the incident sound. $U'(f_x)$ can be calculated from the Fourier transform of the complex wave-distribution function $U(x,z)$ evaluated at $z=0^+$. Thus,

$$U'(f_x)=\int_{-\infty}^{\infty} U(x,0^+)e^{-j2\pi f_x x}dx,$$
$$=2a[\sin(2\pi f_x a)/2\pi f_x a]. \quad (1)$$

Here we have assumed that the intensity of the incident

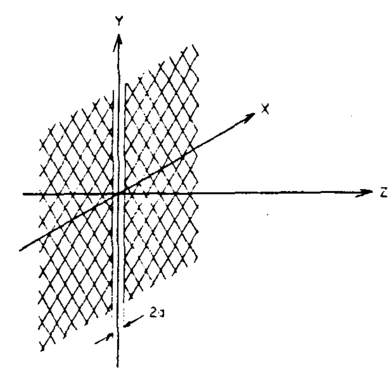

FIG. 1. Acoustic diffracting screen with a long slit as the diffracting aperture.

[1] Cf., M. Born and E. Wolf, *Principles of Optics* (Pergamon Press, New York, 1959), Ch. 11, pp. 556–592.

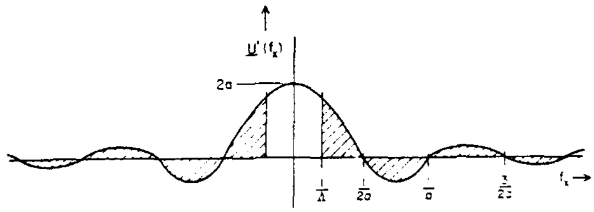

FIG. 2. Spatial spectrum of a slit whose width is less than a wavelength.

radiation is unity. If $2a$ is significantly smaller than Λ, then a substantial portion of the angular spectrum, represented by the cross-hatched region in Fig. 2, will correspond to evanescent-wave components. For this condition, the evanescent components in the region $f_x \geq 1/\Lambda$ are relatively large. These components travel unattenuated along the screen's back surface in the x direction, their amplitude decreasing exponentially with distance in the z direction. Their phase velocity is less than that of normally propagating sound waves, and hence their wavelengths are shorter.

By modifying the slit into a grating, we can arrange to eliminate all components except those within selected, sharply delineated regions of the spectrum. For a grating of $2N$ closely spaced parallel slits, the Fourier angular spectrum is given by

$$U'(f_x) = 4a\frac{\sin(2\pi f_x a)}{2\pi f_x a} \sum_{m=1,3,5\ldots}^{2N-1} \cos m\pi f_x h, \qquad (2)$$

where $2a$ is the slit width and h the periodicity of the grating.

Equation 2 is similar to Eq. 1 except that a finite series of cosine terms multiplies the $\sin x/x$ term. The series has positive or negative peaks at $f_x = m/h$, where m is an integer—*positive* if m is even and *negative* if m is odd. Between the peaks, the series stays close to zero. The larger the value of N, the sharper and narrower the peaks. Thus the rôle of the grating is to intensify certain regions of the $\sin x/x$ curve and to attenuate other regions.

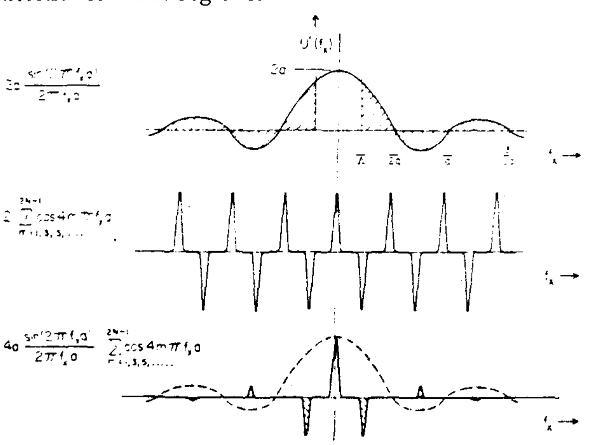

FIG. 3. Spatial spectrum and its factors for grating of the specified design.

Assume that N is large, that Λ is greater than twice the slit width (that is, $\Lambda > 4a$), and that the slit width equals half the periodicity (that is, $2a = h/2$). Then sharp positive or negative peaks exist at 0, $1/4a$, $1/2a$, etc. By examining the curves of Fig. 3, we can see that essentially only one propagating-wave component emerges from the grating (traveling directly along the z axis), and only two large evanescent-wave components emerge. These components are equal in amplitude and travel in opposite directions along the x axis. Hence, they create a standing-wave pattern of significant size near the surface of the grating. For these evanescent components, $f_x = 1/4a$. The other emerging waves (all evanescent) are small because they correspond to the values of f_x that coincide with nulls of the $\sin x/x$ curve or with portions of the curve having small amplitude.

With such a design, the energy is distributed primarily into a wave that propagates in a direction normal to the screen and into evanescent waves that travel along the back of the screen. If the screen is assumed to be positioned with the slits extending horizontally, then the evanescent components, which emerge in pairs, will be moving vertically, one member of each pair moving up and the other down. According to the theory of Bragg diffraction,[2] if the back side of the diffraction grating is illuminated with a properly oriented, converging conical beam of laser light placed downstream from the grating, the zero-order propagating wave will produce two diffracted spots of light symmetrically displaced on a horizontal axis about the position of convergence of the light beam. If the axis of the conical beam is then moved so that it coincides with the center slit and if the half-portion of the beam falling in front of the grating is blocked, one of these spots will disappear. However, the first-order evanescent components will then produce two additional spots displaced vertically from the center position but located slightly further away from the center. Higher-order evanescent components theoretically should produce additional pairs of spots located on the same vertical axis but displaced even further away from the center. In our experiment, however, these components were selected to be of negligible amplitude.

Korpel[3] has shown that Bragg diffracted spots of light may be used for imaging objects placed in the sound beam. Since the resolution of these images is directly dependent on the wavelength of the sound "illuminating" the object, the shorter wavelength of the evanescent components offers the possibility of increased resolution. This assumes that the object is small enough to be placed at a position in the sound field of the evanescent waves where the exponential decay has not decreased the amplitude to an insignificant level.

For the case of a simple slit, the previously described half-conical light beam, oriented so that its axis

[2] R. Adler, IEEE Spectrum 4, 42–54 (1967).
[3] A. Korpel, Appl. Phys. Lett. 9, 425–427 (1966).

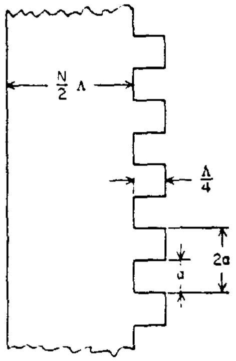

FIG. 4. Acoustic diffraction grating dimensions.

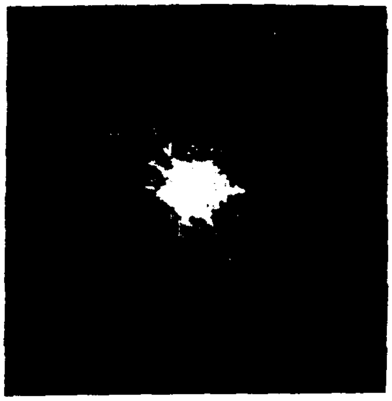

FIG. 5. Image with no sound and grating removed.

coincides with the center of the slit, will interact with components of the angular spectrum of the diffracted sound (assuming that the components are nonzero) to diffract some light. If the sound components are in the propagating region of the angular spectrum, they will interact with components of the light to diffract at various angles. The over-all result will be a circular "fan" of light with an intensity distribution determined by the shape of the angular spectrum. For example, in the case of a slit aperture, if the propagating portion of the $\sin x/x$ spectrum includes some zero crossings, the intensity at the corresponding angles will be zero. If the components are in the evanescent portion of the spectrum, the light is deflected on the vertical axis with an amplitude proportional to the size of the component. Although the detection of an evanescent component from a single slit has not been accomplished at this time, further investigations are proposed.

The design of the acoustic diffraction grating described above was based on an acoustic-transparency concept.[4] The principle used here is that a uniform plate is transparent to sound if its thickness is an integral number of half acoustic wavelengths; it is relatively opaque to sound if the thickness is a quarter of a wavelength longer than this. The theory involved is directly analogous to transmission line and waveguide theory. Using this idea, a grating of transparent grooves was constructed as shown in Fig. 4. The grating was designed for operation in water at 18 MHz. It was made with stacked, alternate pieces of stainless steel 150 μ long (one-half wavelength) and 225 μ long. Each piece was 40 μ thick, giving a grating periodicity of 80 μ.

Experimental results have verified the existence of the hypothetical acoustic evanescent waves. The experiment consisted of aligning the grating in an acoustic cell and passing a properly centered laser beam through the cell. Figure 5 is a photograph of the light at the position of convergence of the laser beam with the sound off and the grating removed from the cell. This photograph shows the background light that is scattered by the water and the optical elements of the system. The sunburst image is mainly due to diffraction effects and faults in the lenses. With the grating placed in the cell, the entire unit was aligned relative to the cone of light such that the axis of the cone coincided with the center slit of the grating. The front half of the light cone was then blocked out. Figure 6 shows the image obtained with the grating in place and the sound turned on. There are four main diffracted spots displayed. The upper spot on the vertical axis is that due to the evanescent component. The spot in the lower part of the Figure is the other predicted spot of the matching evanescent component. It is off axis, probably because of local bands in the grating and alignment difficulties of the grating with respect to the transducer.

The two spots on the horizontal axis are from the propagating component. The right spot is brighter than the left because of the alignment of the acoustic cell with respect to the laser beam. As explained previously, if the alignment had been perfect, only one spot (the right spot) would have been present. The small fan of light observed in the first and third quadrants is from propagating sound due to scattering from bubbles of air trapped in the grooves of the grating, edge effects unaccounted for in the design, and local inconsistencies in the fabrication of the grating. The center spot is streaked to the left because of diffraction effects as the light skims behind the grating. This effect has caused

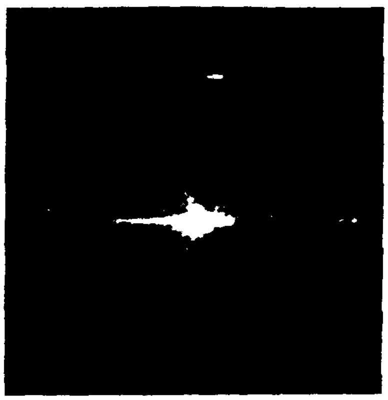

FIG. 6. Image with Bragg diffracted spots (sound on, grating in place).

[4] G. Wade, C. J. Landry, and A. A. deSouza, *Acoustical Holography* (Proc. First Int. Symp. Acoust. Holography), A. F. Metherell, H. M. A. El-Sum, and L. Larmore, Eds. (Plenum Press, New York, 1969).

the apparent point of convergence to be shifted in the photograph. Measurements described below are taken from the actual point of convergence of the laser beam.

Measurements of the distances of the spot locations from the center gives an indication of the relative wavelengths of the components. For our experiment, the theoretical ratio of the wavelength of the propagating component to the wavelength of the evanescent component is 1.05. The measured ratio of distances of the corresponding spots (which should be equal to the wavelength ratio) was 1.1. Measurements of the intensities of the spot due to the evanescent component as one moves the diffracting screen away from the light beam enables computation of exponential decay. The measured experimental value was 1.3×10^3 m^{-1}, which compares with the theoretical value of 3.7×10^3 m^{-1}.

In summary, experimental verification of the scalar wave-theory prediction of evanescent waves has been carried out for acoustical waves in water. The components were isolated by the grating design. The waves were detected by Bragg diffraction of laser light by the evanescent waves. Experimental measurements verify the wave theory within the limits imposed by the errors of the fabrication of the grating and the alignment difficulties.