Angular Selectivity and Acoustic Sensitivity in Optical Heterodyne Ultrasonic Image Converters*

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Abstract

In the optical heterodyne system for acoustic image detection proposed by Massey, the effects of angular selectivity on the measurable acoustic intensity are discussed.

Results of the analysis show that the measurable acoustic density is strongly affected by the angle of wavefronts between the local-oscillator beam and the reflected signal beam frequency-modulated by sound waves and if the optical devices are in good alignment for all positions of scanning the signal beam, the optical heterodyne method has a minimum measurable acoustic density comparable to that obtained using the best of practical alternating methods now available.

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1. Introduction

Recently, Massey suggested a means for acoustical-to-optical image conversion in which he uses optical heterodyne detection to measure and display the frequency shifted component of light reflected from a diaphragm of surface driven by the incident sound field.[1] Sensitivity to low sound levels in the system is comparable to the best alternate methods for much of the frequency spectrum in acoustic holography and ultrasonic visualization techniques. The most difficult point, however, is the fact that optical heterodyning exhibits angular selectivity properties, so that minimum measurable acoustic intensity increases.

In the present paper, the problems on the effect of angular selectivity on the acoustic sensitivity in the optical heterodyne ultrasonic image converter are discussed in the following paragraphs.

2. Angular Selectivity and the Minimum Measurable Acoustic Intensity

The basic elements of the optical heterodyne system for acoustic image detection are shown in Fig.1. The laser beam at a frequency ω_0 is processed in

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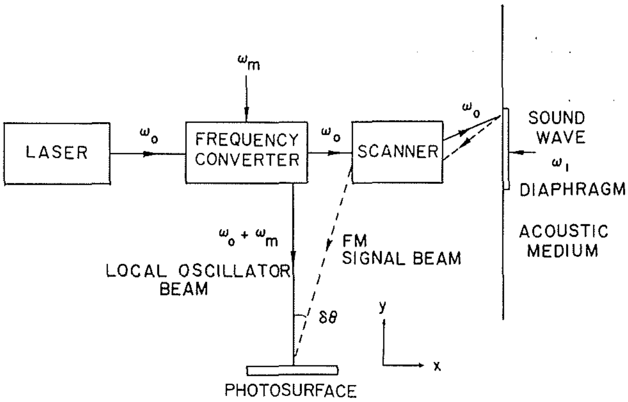

Fig. 1. Schematic diagram of optical heterodyne system for acoustic image detection.

the frequency converter such as the Bragg diffraction device,so that approximately half of the optical power emerges at a frequency of $\omega_0+\omega_m$ and the remainder is at ω_0. The unshifted light is delivered to the scanner and the shifted $\omega_0+\omega_m$ portion serves as the local-oscillator beam. The scanner directs the beam at frequency ω_0 onto the reflective diaphragm at the end of the liquid acoustic medium. The diaphragm is driven at ω_1 by sound waves which have been scattered by the target. The sound source is a transducer excited at the frequency ω_1 by a signal generator. Light reflected back into the scanner by the moving diaphragm has a frequency-modulated spectrum due to the phase modulation by the amplitude of the vibration $Z(p)$ at point p on the diaphragm

$$\phi(t) = 2kZ(p)\sin \omega_1 t \tag{1}$$

where k is the phase constant of the laser beam at frequency ω_0. The spectrum of reflected signal beam is centered on the frequency ω_0. When the optical devices are properly aligned the local-oscillator and reflected signal beams produce a beat at the square-law photosurface.

For simplicity, it is assumed that an equivalent point of the origin of the local-oscillator beam is on the line perpendicular to the photosurface and passes through the detector center and an equivalent point of origin of the reflected signal beam is on the line at the very small angle $\delta\theta$. The photosurface is a strip of width d in the x-direction and uniform in the z-direction. It is also assumed that the two beams have the same optical modes, which are identically polarized and each beam is effectively a plane wave. At high frequencies the magnitude $Z(p)$ is always small compared to the optical wavelength, thus it follows that the vibration information is contained in the two sideband currents whose rms amplitudes are[1)]

$$i_{SB} \approx 2D\sqrt{I_{lo} I_s}[kZ(p)], \tag{2}$$

where I_{lo} and I_s are the photocurrents which would be present due to the local-oscillator or reflected signal beam alone, respectively. The quantity D is the directivity factor which shows angular selectivity properties in optical heterodyne detection. When the local-oscillator and the reflected signal beams are uniform plane waves, the directivity factor D_1 is given by

$$D_1 = \mathrm{sinc}\,(\pi d\delta\theta/\lambda), \tag{3}$$

where λ is the optical wavelength and the notation sinc $x = (\sin x)/ x$ was used.[4),5)] If two beams are Gaussian plane waves, the directivity factor D_2 in the case where the distribution length is small compared with the photosurface width is shown as

$$D_2 = \exp[-(\pi u_0 \delta\theta/\lambda)^2/2], \tag{4}$$

where it is assumed that the distribution length of two beams has the same value u_0 and they are directed towards the same incident point on the photosurface.[6)]

If the optical signal is strong, the dominant process will be shot noise and the rms noise current is

$$i_n = [2e\,(I_{lo}+I_s)B]^{1/2}, \tag{5}$$

where e is the electronic charge and B is the circuit bandwidth which must be large enough to accommodate the viedo information rate due to a frame time and resolution elements. If $I_{lo} = I_s = \lambda\eta e P_0/2hc$, where η is the effective quantum efficiency,[7)] h is the Planck's constant, c is the speed of light and P_0 is the total laser power, a final expression for the displacement sensitivity is given by

$$Z_{min} = (hc\lambda B/\pi^2\eta D^2 P_0)^{1/2} \tag{6}$$

For simplicity, in the case where the diaphragm is driven in a thickness-resonant mode the minimum measurable acoustic intensity J_{min} can be shown by

$$J_{min} = 2\rho v f_1{}^2 hc\lambda B/D^2 Q^2 \eta P_0, \tag{7}$$

where ρ is the density of the acoustic medium, v is the velocity of sound, f_1 is the frequency of sound wave and Q is the factor which represents the amplitude enhancement due to the diaphragm resonance.

3. Discussion

As an illustration of the effect of angular selectivity on the sensitivity of ultrasonic image converters, let us consider then numerical example with parameters used by Massey.[1)] When the sound wave is incident on a diaphragm with water in the acoustic medium and air on that side of the disk, on which the laser beam

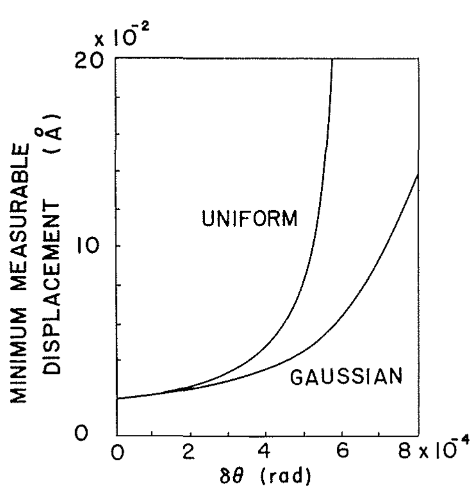

Fig. 2. Minimum measurable displacements as a function of $\delta\theta$ in uniform and Gaussian plane waves.

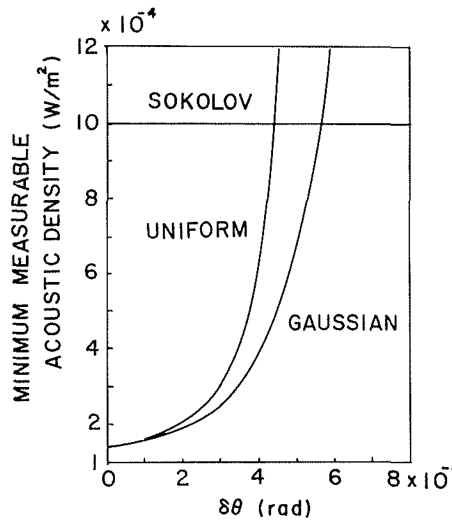

Fig. 3. Minimum measurable acoustic density as a function of $\delta\theta$ in the uniform and Gausssian plane waves. The sensitivity of Sokolov tube is also shown.

is incident and a frequency stabilized He–Ne laser[8] is used, plots of the displacement sensitivity for uniform and Gaussian plane waves are shown in Fig. 2. It was assumed that $d = 0.5$ mm and $u_0 = 0.5$ mm. It is apparent that as $\delta\theta$ increases, the minimum measurable displacement of the diaphragm increases and goes infinity at $\delta\theta = 2\pi \times 10^{-4}$ rad. Plots of the minimum measurable acoustic density as a function of $\delta\theta$ in the case of the same parameters are presented in Fig. 3. The sensitivity of the Sokolov-tube[9] is also shown in this figure. The Sokolov-tube technique is basically an image orthicon with a piezoelectric rather than a photoemissive surface and induced charges on the piezoelectric are read off by a scanning electron beam and the sensitivity is about 10^{-3} W/m^2, moreover, there is no critical angular sensitivity. The optical heterodyne system, however, exhibits the angular selectivity property. Namely, the angle of wavefronts between two beams increases by scanning the reflected signal beam and the minimum measurable acoustic density increases. It should be noted that in the case of Gaussian plane waves the minimum acoustic density never goes completely to infinity but approaches this value as $\delta\theta$ is made large.

The effect of angular selectivity on sensitivity of image converters in two-dimensional scanning can easily be estimated[10] and the effect of incident points of reflected signal and local-oscillator beams may also be calculated in Gaussian plane waves.[11] The distribution of effective quantum efficiency is not uniform over the photosurface and this affects the minimum measurable acoustic density in optical heterodyne detection of ultrasonic image converters.[12]

4. Conclusions

In the optical heterodyne detection system for acoustic image detection the directional characteristics and the measurable acoustic density were discussed. Results of the analysis show that the optical heterodyne method has measurable acoustic densities comparable to those obtained using the best of the practical alternating methods now available, if optical devices are in good alignment for all portions of the scanning signal beam.

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