SUPERRESOLUTION IN ULTRASONIC IMAGING

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ABSTRACT

Since it has been demonstrated that superresolving acousto-optical systems can be realized the question of their applicability to the imaging of other than point sources arises. This paper reviews the experimental and theoretical evidence for the possibility of superresolution and explains why it is of particular interest to ultrasonic imaging. The problems relating to the limits imposed by information theory to the imaging of distributed objects is examined and a method of obtaining the necessary spatial bandwidths is discussed.

INTRODUCTION

In an earlier publication\(^1\) we described experimental evidence demonstrating the realization of superresolved images of a small ultrasound source. The image was produced by a lens which had very small aberration and was self-shaded by the interfacial effects at the refracting surfaces. This demonstration indicates that it is possible to think in terms of superresolving imaging of point sources at least under some conditions. The practical usefulness of superresolution is, however, another matter altogether and the prospects for the application to extended objects is the subject of this paper.

The need for superresolution in imaging arises from the problems of absorption of ultrasound at high frequencies. Higher resolution at present is only obtainable in many circumstances by increasing frequency but this degrades the signal to noise of the received signal, consequently there comes a point at which higher resolution becomes impossible. In ultrasonics superresolution may allow better resolution by allowing imaging at lower frequencies with signal to noise ratios which are better than those which would be obtained in matching conventional systems. The hope for this approach depends on the fact that absorption of ultrasound increases at least as the square of the frequency i.e. signal to noise degrades as the inverse of this ratio. The ratio of signal to noise in superresolving sys-
tems is not sufficiently explored for the signal to noise ratio to be expressed as a function of frequency but elementary arguments suggest that the relationship may be linear in some circumstances. Put directly the signal to noise ratio associated with a resolution gain equivalent to a doubling of frequency may be twice as good in a superresolving system. If this is so then superresolution will allow images resolution which could not be obtained otherwise. This being said such imaging requires a process by which the simple Nyquist conditions which lead to aliasing are circumvented.

HISTORICAL BACKGROUND

Apart from the use of diffraction patterns to obtain data about a source (e.g. stellar interferometers) the first clear recognition of super-resolution appears to be that of Luneburg who, in 1944, showed that the Airy diffraction integral:

$$F(x,y,z) = \frac{1}{2\pi} \int \phi(p,q) e^{ik(Wxp+yq+zr)} dp dq$$

allowed a multiplicity of solutions and that the classical solution was simply that which gave the central lobe the maximum energy. Luneburg gave other solutions which reduced the halfwidth of the main lobe to satisfy particular conditions and which were readily applicable to the diffraction integral. Later the problem was addressed in a series of papers by Toraldo di Francia particularly in relation to radar beamforming. He showed that there was an arithmetic technique which allowed the central lobe to be of any arbitrary width and provided control of the sidelobe maxima. This work led to a bitter controversy in which it was claimed that the technique advanced was in conflict with the uncertainty principle, however it was finally demonstrated that zero beam width was coincident with zero energy in the beam and the approach to zero beam width led to conditions which satisfied that principle. Since that time much work has been done on various aspects of apodization. Resolution for ultrasonic imaging can use these techniques but recognition of the fact that the work of the pioneers necessarily invoked energy whereas in ultrasound pressure or velocity can be used. The work relating to the control of the diffraction pattern which has just been described is unfortunately only one aspect of the problem and applies particularly to a point source. In general an extended array of sources constitutes the objects we need to image and we arrive at a situation in which it is necessary to consider the interaction of the various main and sidelobes associated with this array. This problem was considered by Abbe and Rayleigh who used a regular array to determine the resolving power of microscopes. Much later with the advent of Fourier optics the problem was revisited and considered in terms of the spatial frequencies of wave fronts and the bandpass of the aperture involved. This development was associated with the discoveries in information theory which allowed the Nyquist sampling theorem to be applied (and arrive at Rayleigh's conclusion by another method). The new treatment was extended to describe the use of filters in the Fourier domain in order that particular images could be recognized, such filters in effect being apodization devices.