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A HYBRID COMPUTATIONAL METHOD FOR UNDERWATER ACOUSTIC SCATTERING

Elizabeth A. Orme (1), P.B. Johns (2) and J.M. Arnold (3)

(1) Smith's Industries Ltd., Cheltenham
(2) Dept. Electrical & Electronic Engineering, University of Nottingham, University Park, Nottingham NG7 2RD.
(3) Dept. Electrical & Electronic Engineering, University of Glasgow, Glasgow.

INTRODUCTION

The problem of target recognition in underwater acoustics is one of analysis of scattered waves to produce sufficient recognizable features. In common with applications such as ultrasonic medical diagnosis, non-destructive testing and prospecting, the aim is to produce an image of the target, and much is published on the subject [1]. One way of proceeding is based simply on timing the reflections contained in the received signal and this has obvious limitations such as variation of velocity in various media and multiple reflection phenomena. Another way of proceeding is to use a computer simulation of the scattering process for a target with variable parameters and to adjust these parameters in order to produce a match between the simulated received signal and the actual one. This paper is concerned with the latter approach and in particular concentrates on a proposed technique for computer simulation of acoustic scattering.

In circumstances where the target and distances to it are reasonably comparable to the interrogating wavelength, it is possible to carry out the scattering analysis by numerical methods which discretise the target and the propagation space. This may be done through a mesh discretisation process such as finite differences or finite elements. A method known as transmission-line modelling (TLM) has been developed at Nottingham University, and this technique in conjunction with optimisation has also been used for imaging [2]. Advantages of a mesh method such as TLM are that it models target features in considerable detail, operates just as readily in three dimensions as two, and is capable of dealing with complicated scattering processes.

However, where the target and propagation distances involved are small compared to the interrogating wavelength, as is usually the case with underwater acoustics, mesh methods run into difficulty. This is because internodal distances must be a fraction of a wavelength resulting in large inefficient meshes. Often geometrical ray methods are used for computer simulation under these circumstances [3]. Ray techniques are particularly suitable for long range propagation where acoustic parameters vary slowly on the scale of the wavelength, but they do have limitations in that it is not easy to analyze detailed local diffraction scattering in three dimensions.

The advantages and disadvantages of these different approaches suggest the possibility of combining the two techniques into a hybrid method. The central problem is then that of connecting the geometrical ray and discrete mesh representation for the acoustic fields. The paper describes the work done in investigating the excitation of a TLM mesh from rays and the detection of wavefronts on the mesh for launching of new rays.

TLM AND WAVEFRONT EXCITATION

The transmission-line modelling (TLM) technique models the propagation mechanism of waves by filling space with a network of transmission-lines. This has the effect of rendering a problem discrete in both space and time, since the exact solution of the network is in effect a time stepping numerical routine.

Consider a graph consisting of n nodes connected by b branches, with numbers termed pulses travelling between nodes along the branches. The time taken for a pulse to travel between any node and a neighbouring node along a transmission-line is one timestep. At the time of the kth timestep there are 2b pulses ($\underline{V}^i$) incident on the nodes and these are instantaneously scattered by the nodes into 2b reflected pulses ($\underline{V}^r$).

Thus,

$$ {}_k\underline{V}^r = \underline{S} \; {}_k\underline{V}^i \qquad (1) $$

where $\underline{S}$ is a scattering matrix.

It takes one timestep for these reflected pulses to travel along the transmission-lines and become incident on neighbouring nodes.

Hence,

$$ {}_{k+1}\underline{V}^i = \underline{C} \; {}_k\underline{V}^r \qquad (2) $$

where $\underline{C}$ is the connection matrix which describes the topology of the transmission-line graph.

Repeated operations of equations (1) and (2) constitute the TLM procedure.

In modelling acoustic waves the topological laws and the branch laws ensure the conservation of mass and energy and equivalances can be drawn between across variables and the pressure field and through variables and the displacement. It is generally convenient to arrange the graph topology to correspond to a simple cartesian co-ordinate system, although this is not essential. Different media and their reflecting, or partially reflecting, boundaries are modelled according to the parameter chosen for the transmission-lines.

Geometric rays travelling through space are considered to represent the magnitude and direction of plane impulsive waves. Nodes on the mesh are excited corresponding to the impulsive wavefront which, for the two dimensional investigations described here, consists of a line travelling towards the mesh as shown in Figure 1. Two techniques have been used for excitation:

(a) Insertion of the entire wavefront at a single instant in time at nearest nodes, or (b) at boundary nodes over many timesteps at the nearest timestep. Both techniques have been found to be satisfactory, the former requiring a somewhat larger mesh, while the latter is more difficult to use.

DETECTION OF WAVEFRONTS ON THE MESH

Following the excitation, pulses travel around the TLM mesh and the entire network soon becomes filled with pulses. Detection of scattered wavefronts by simple observation of field values is impossible and in this investigation the processing of the field values at the nodes has been carried out using two-dimensional Fourier transforms[1].

Consider a continuous field f(x,y) in two continuous space dimensions containing scattered waves. This is transformed to F(p,q) in continuous two-dimensional $\underline{K}$ space, where,

$$\underline{K} = p\,\underline{i} + q\,\underline{j} \tag{3}$$

through

$$F(p,q) = \int_{-\infty}^{\infty} F_x(p,y)\, \exp(-j\,q\,y)\, dy \tag{4}$$

where

$$F_x(p,y) = \int_{-\infty}^{\infty} f(x,y)\, \exp(-j\,p\,x)\, dx \tag{5}$$

Suppose that f(x,y) has a component f_o propagating at an angle ϕ to the x axis with amplitude A and velocity v as shown in Fig. 2(a),

$$f_o(x,y) = A \exp\left[j(\omega t + p_o x + q_o y)\right] \tag{6}$$

and $p_o = \frac{\omega}{v} \cos\phi$ and $q_o = \frac{\omega}{v} \sin\phi$

Equation 5 becomes

$$F_x(p,y) = A\,\delta\,(p - p_o)\, \exp\left[j(\omega t + q_o y)\right] \tag{7}$$

and equation 4 becomes

$$F(p,q) = A\,\delta\,(p - p_o,\, q - q_o)\, \exp(j\omega t) \tag{8}$$

Thus f_o is transformed to a delta function in $\underline{K}$ space with co-ordinates (p_o, q_o) as shown in Figure 2(b), and,

$$\tan\phi = q_o/p_o$$

An impulsive wavefront propagating at angle ϕ, therefore, transforms to a line of delta functions along the locus OA shown in Figure 2(b). The position of the impulsive wavefront is associated with the relative phase of these delta functions.

The field f(x,y) is taken only at the nodes of the mesh and so f(x,y) is in sampled form. The integration is performed numerically through discrete Fourier transforms or standard fast Fourier transforms, and the data in $\underline{K}$ space is also produced in sampled form. The effect of using a finite sized mesh on which to derive f (x,y) is to produce pulses of sin x/x shape rather than delta functions.

The problem of locating the directions of plane waves on the TLM mesh is reduced therefore to the process of locating peaks in sampled $\underline{K}$ space.

NUMERICAL EXPERIMENTS

Experiments were first carried out using a one-dimensional space Fourier transform by making an observation in $\underline{K}$ space along a single line of constant p. The aim is to detect impulsive waves and the above analysis shows that there is enough information in such an observation to determine a wavefront direction.

Various experiments to detect reflected waves using the one-dimensional procedure were carried out. An example used a wavefront launched at an angle of 27 degrees into a 10 x 20 mesh which contained a perfectly reflecting boundary. After 16 timesteps an 8 x 8 block was selected which contained reflected wavefront data, although it was no longer possible to observe the wavefront within the TLM impulses. After performing the space Fourier transform a wave direction of -28.5 degrees was obtained. Experiments were also carried out on a diffracted wavefront to test the ability of the process for detecting segments of a curved wavefront. Again successful results were obtained but with accuracy decreasing as the size of the observation data block is reduced, and also as the number of timesteps is increased. It was also found that, with the value of p chosen, it was difficult to detect wave directions approaching $\pm \pi/2$.

Further experiments were carried out using the entire two-dimensional $\underline{K}$ space which was calculated in sampled form using a Fast Fourier Transform routine. A half-plane was placed within a TLM mesh and a line of impulses launched into the system. In this case plane and diffracted wavefronts were present and it was found that both could be detected and angles of observation measured.

From these experiments it was observed that high frequency distortion of the results was occurring. This was particularly noticeable with the curved wavefronts which were being represented on a cartesian mesh. This introduced quantisation errors which were compounded as the number of TLM iterations carried out was increased. It is these quantisation errors which are introducing high frequencies into the system.

To reduce high frequency effects the inter-nodal spacing of the TLM mesh was reduced. This produced a corresponding increase in accuracy of any curved wavefront representation. Also, the number of TLM iterations carried out was minimised by carefully considering where an incoming wavefront must be launched into the TLM mesh. Lastly, the TLM impulse response was low pass filtered before carrying out the transform routine. By introducing all of these measures a considerable increase in the accuracy of results was achieved. However, this also increased computer storage and running time requirements.

The above TLM and transform procedure is now being studied, with the modifications included, for scattering from more complicated geometries.

CONCLUDING REMARKS

A hybrid computer simulation method which combines the advantages of ray and mesh techniques should be very useful for scattering geometries which are large compared to the wavelength. The preliminary work described in this paper indicates that methods are available for connecting rays to the mesh, and for generating rays from the mesh. The two-dimensional space Fourier transform for detection of wavefront directions is clearly promising and warrants a detailed investigation.

The hybrid technique envisaged may be used to enhance an existing ray tracing computer program. Target local geometrical disturbances which might be difficult to analyse by rays can be surrounded by a relatively small TLM mesh which then generates diffracted rays which propagate back to the receiver.

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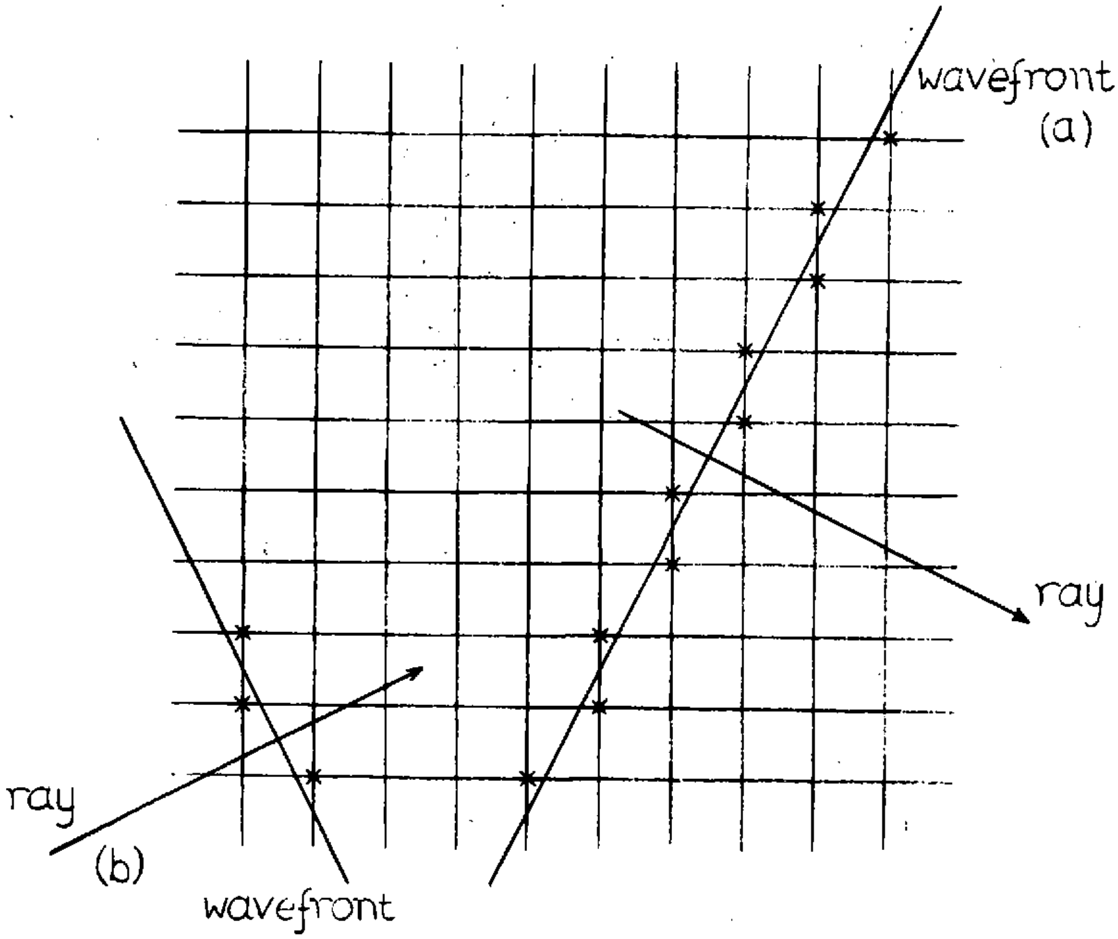

(a) Excited at nearest node at one time instant.

(b) Excited at boundary at nearest time instant.

Figure 1 Excitation of Nodes from Rays

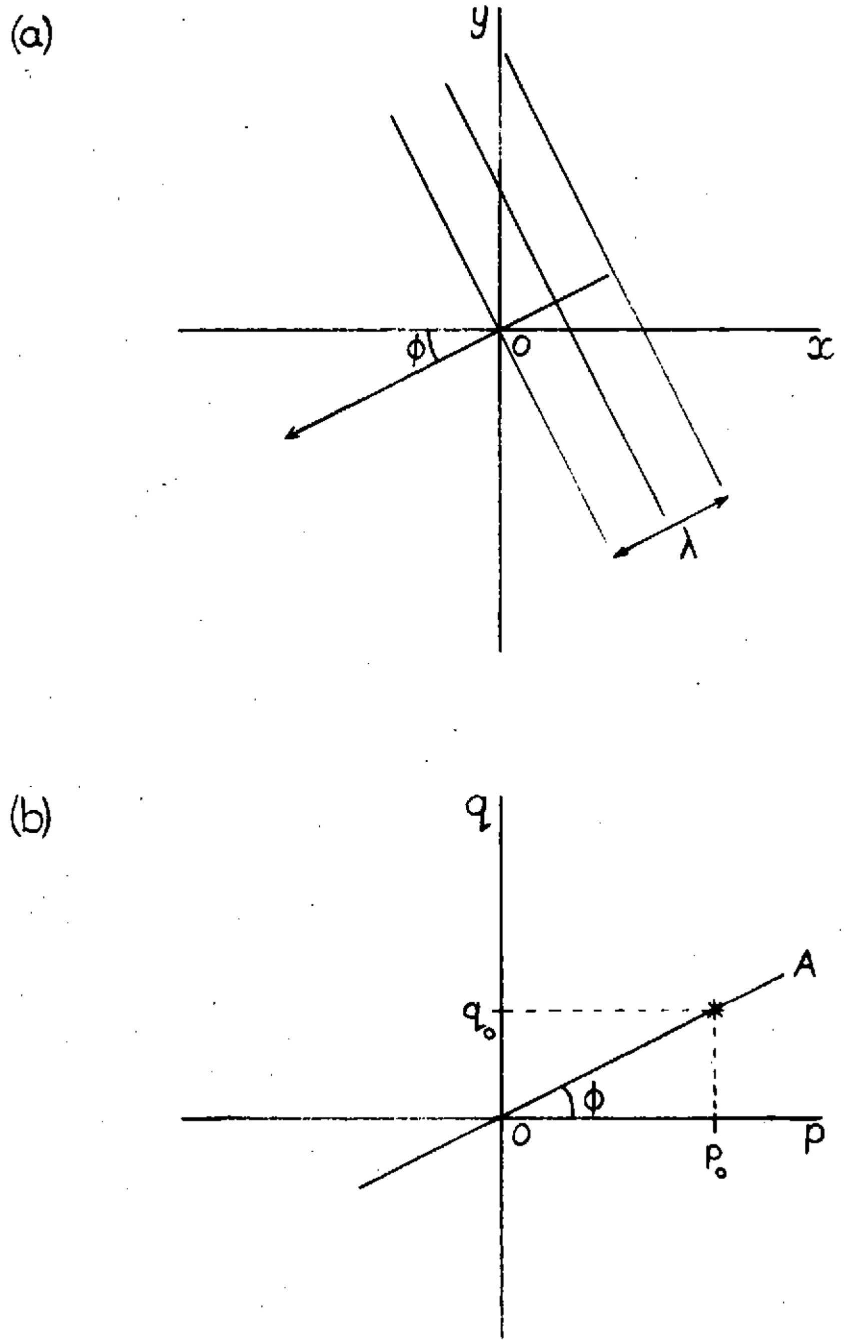

Figure 2 A Component Wave and its Transform in K space