Design and implementation of an acoustic simulator of noise level distribution in the ocean

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***Abstract*—This is the abstract text.**

I. Introduction

With the increase of human activities in coastal areas, many different type of sources of noise are now present in the ocean. Among these sources, one can cite sonars, seismic exploration, underwater industrial processing, civil engineering projects, commercial and recreational transportation to cite a few. Recently, a new type of source of noise associated to deep sea mining has appeared. All these sources may contribute to the increase of noise level and have to be addressed. As a consequence, the accurate numerical simulation of acoustic wave propagation in the ocean is very important in order to be able to predict the distribution of noise level generated by all the types of sources. It will allow the generation of accurate acoustic maps which will help to assess the impact of these sources on marine life. Many acoustic propagation models are available. Under some assumptions, they all are able to propagate the sound field over long distances. Nevertheless, the underlying hypothesis behind these models often leads to some lack of accuracy. This is the price to pay to be able to propagate over long distances with a reasonable computational cost. On the other hand, accurate numerical modeling requires a computational burden which can be heavy and not always realistic. For instance, numerical methods based on a finite spectral-element method can provide very accurate solutions to wave propagation problems for complex geometries and rheologies (acoustic, elastic, viscoacoustic, viscoelastic…) but still require the use of high performance computing to be able to provide a result for a reasonable time lapse. Furthermore, for long ranges, the computational cost is so important that obtaining a numerical result is not possible even using a super computing center. We present a tool which aims at being a compromise between accuracy and feasibility for the generation of acoustics maps of noise distribution in the ocean. In general, the main difficulty is connected to the correct taking into account of the source characteristics because source implementation in numerical codes dedicated to ocean acoustics is often simple. This is the reason why we chose to evaluate the sound field in the vicinity of the source by means of an accurate numerical method such as the finite spectral-element method and to couple the results provided by this numerical method to more classical numerical models. We will consider the coupling with a ray tracing software and with a code implementing the parabolic approximation method. In this way, the spectral element method will act as a starter for the parabolic equation method. For the ray tracing software, it will provide an initial directivity. Some results of the implementation of such a numerical solution for different configurations are presented. We will show that complex source configurations in complex environments can be considered leading to the possibility of generating more accurate acoustic maps.

II. Short description of numerical models

A. *The spectral-finite element method*

In this section, we recall the main characteristics of the spectral finite element method and we focus only on some of its most important features. For more details the reader is referred to references [1], [2], [3]. The spectral-element method (SEM) is based upon a high-order piecewise polynomial approximation of the weak formulation of the wave equation. It combines the accuracy of the pseudospectral method with the flexibility of the finite-element method. In this method, the wavefield is represented in terms of high-degree Lagrange interpolants, and integrals are computed based upon Gauss-Lobatto-Legendre quadrature. This combination leads to perfectly diagonal mass matrix, which in turns leads to a fully explicit time scheme that lends itself very well to numerical simulations on parallel computers.

It is particularly well suited to handling complex geometries and interface conditions. As a consequence, the accurate simulation of surface wave propagation is straightforward without any additional cost. The use of a pseudospectral method also leads to the generation of coarser meshes. The typical element size that is required to generate an accurate mesh is of the order of λ, λ being the smallest wavelength of waves travelling in the model. This comes from the fact that each spectral element, when using the SEM with a polynomial degree of $N = 4$, which is a typical value, contains a subgrid of $(N + 1)$*2 = 5 x 5 Gauss-Lobatto-Legendre discretization points and requires about 5 points per minimum wavelength of the problem under study. Very distorted mesh elements can be accurately handled. Complex models that include fluid, elastic, viscoelastic, anisotropic or porous media can be modeled, making the SEM a method of choice for the numerical modeling of wave progagation through various types of media encountered in underwater acoustics. Results have been thoroughly validated with analytical codes and are used by many researchers in seismology all over the world. Finally, the SEM is well-suited for parallel implementations on supercomputers as well as on clusters of GPU cards by using the Message-Passing Interface (MPI) library and overlapping communications with calculations to hide their cost. This is an important feature for high-performance computing.

The spectral-element method, because of its ability to handle coupled fluid-solid regions, is a well-adapted tool for performing wave propagation simulations in underwater acoustics in the time domain. Several publications have already used its potential in this domain [5], [6], [7]. Moreover, it is also known for being accurate to model surface and interface waves such as the Stoneley-Scholte wave. In this work, we will present a new application domain where the use of the SEM can bring new perspectives for the modeling of wave propagation.

B. Parabolic equation method and ray tracing

The parabolic approximation and ray theory are useful tools for the modeling of wave propagation in underwater acoustics. They have their own advantages and drawbacks. The reader is referred to the book of Jensen et al. [4] where both methods are described in details. To resume, the parabolic approximation is a one-way only wave propagation method which has an angular limitation which can be overcome using high order approximations of the square operator while ray theory is a high-frequency approximation of the wave equation which may have difficulties for the calculation of amplitudes especially in regions where caustics can occur. Nevertheless, they are both very useful tools, the ray tracing method is a very fast method. The parabolic approximation is slower but in any case much faster than the spectral-element method.

III. Method for coupling

In this section, we indicate how the coupling is performed for the simulation of the sound propagation in the deep ocean at long ranges. First, in order to perform the coupling with a ray tracing software, we consider a set of receivers situated on a circle at a distance of 50 m from the source. The distance is chosen so that it is far enough from the source itself and the possible structure which may modify the sound field. It will provide the directivity in water associated to the system composed of the source and its environment and a starting field for the ray tracing software. An example is indicated in Figure1.

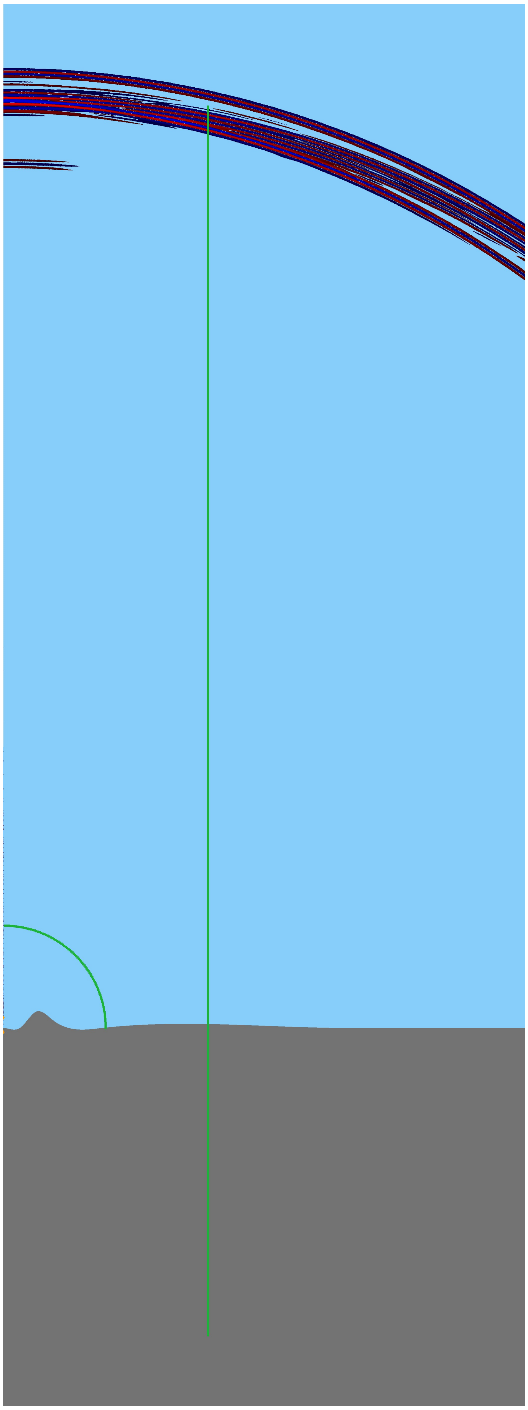

Fig. 1. Snapshot of the sound field calculated with a spectral element method for a source situated in the vicinity of a hole. The two green lines represent the two receiver arrays which are used as a starter for the ray tracing and for the parabolic equation method.

For the generation of the starter for the parabolic equation, it is necessary to calculate the sound field on a vertical line covering the entire vertical extension of the computational domain. Since performing a time-domain full-wave numerical simulation for the frequencies we would like to consider, for the entire water column plus the sediment, is not possible even for short ranges, we have to design a limited domain both in range and depth for which the numerical calculations are reliable. The range limitation is not a problem. It will simply give the position of starting range for the parabolic equation method. It must be far enough from the source so that we take into account all the complex interactions which may occur in the vicinity of the source. The limitation with depth has a different impact on the numerical calculations. It will limit the aperture of the wavefield which will be incorporated in the starter. Since the parabolic equation has a limited aperture validity, it is therefore not necessary to incorporate, into the starter, the wavefield up to the surface. A limited portion is sufficient. Figure 2 indicates the value of the angular limitation if we consider a limited vertical line situated at a 100 m horizontal distance from the source. Calculating the wavefield up to a distance of 400 m above the interface gives an angular aperture of [0°, 76°] which is typically the angular capability of a parabolic equation using a Padé approximant of order 5. This aperture is sufficient for the calculation of transmission losses at long ranges. For the angular limitation in the sediment, we consider only receivers up to a depth of 100 m which corresponds to an angular limitation of 45°.

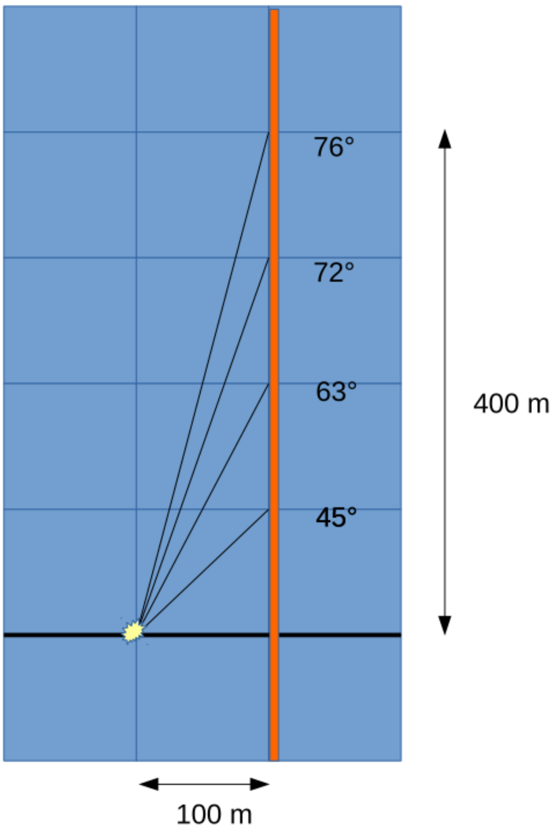

Fig. 2. Angular limitation associated to the use of a limited vertical array as a starter of the parabolic equation

The wavefield is first calculated in the time domain using a spectral element method. We ensure that all wavefronts have been captured by all receivers by taking a time duration which is long enough. Then, we perform a fast Fourier transform of the two receiver sets independently. The first receiver set will serve as an input for the ray tracing software. The second set will be used to create the starter for the parabolic equation solution. Working in the time domain allows us to work for several frequencies simultaneously. As a source signal, we consider a Ricker wavelet with a dominant frequency equal to 500 Hz. It means that we are able to get the starters for a frequency up to 2.5 kHz. The values we obtain along the limited vertical line are then padded with the necessary number of zeros to cover the entire water column and the sediment layer.

IV. Results

As indicated in Figure 1 we consider a source placed 5 m above an interface situated at a depth of 1000 m. We performed several numerical simulations with a flat interface and with a hole in the vicinity of the source with either a fluid or a solid sediment. The density and the sound speed of longitudinal waves are rho = 4000 kg/m3 and Vp = 4800 m/s respectively. For the elastic sediment, we simply add to the fluid sediment characteristics a sound speed for the shear waves equal to 2600 m/s.

The water medium is considered as a homogeneous medium for the full-wave simulations. For the simulations made with the ray tracing software and the parabolic equation method we have included a sound speed profile of the Munk type in the water column.

A. Coupling with the parabolic equation method

The parabolic equation method is implemented using a 5th order Padé approximation of the square root operator. Additionaly, in order to eliminate the reflections from the bottom of the domain, we add a PML layer. The results are presented in the following figures where we provide acoustic maps of pressure levels for 50 Hz, 100 Hz, 250 Hz and 500 Hz.

For a fluid sediment, it can be seen that the presence of a hole affects the pressure levels. The modifications of the directivity of the source induced by the hole differ with the value of the frequency but the general tendency is that more energy is sent towards the vertical direction.

Similarly, for an elastic sediment, we can see the same behaviour as for the fluid sediment with more energy sent towards the vertical direction when a hole is present. It can also be seen that the presence of an elastic sediment modifies the way the energy is distributed into the water column. Taking into account the elastic nature of the sediment is thus important. This is particularly important for deep sea mining because, at the depths where it is operated, the value of the sound speed of the shear waves is high and then cannot be neglected.

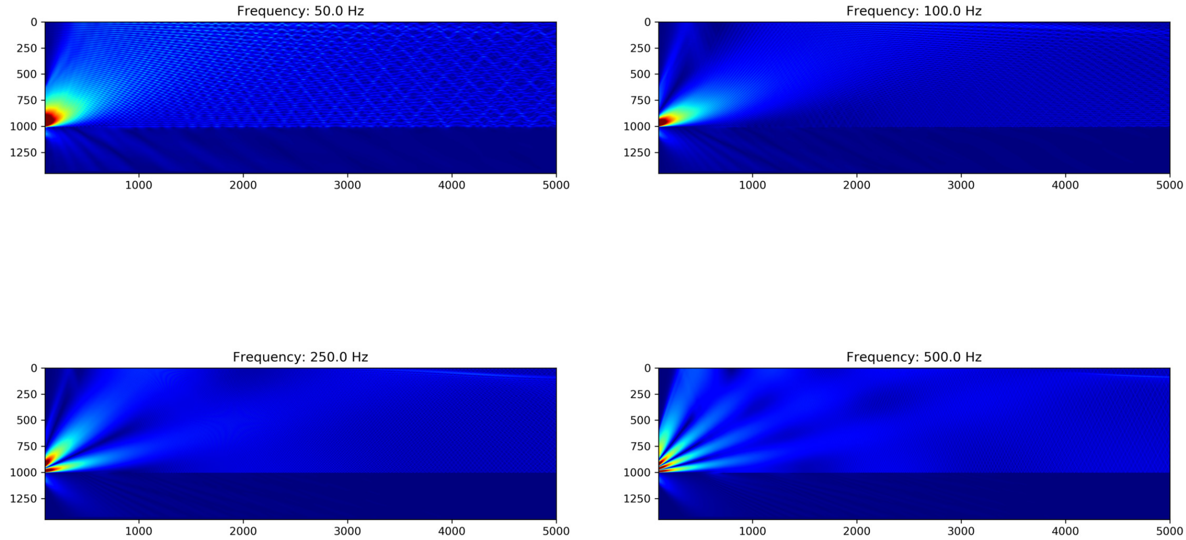

Fig. 3. Acoustic maps of pressure levels calculated with the parabolic equation method for a source above a flat interface with an fluid sediment

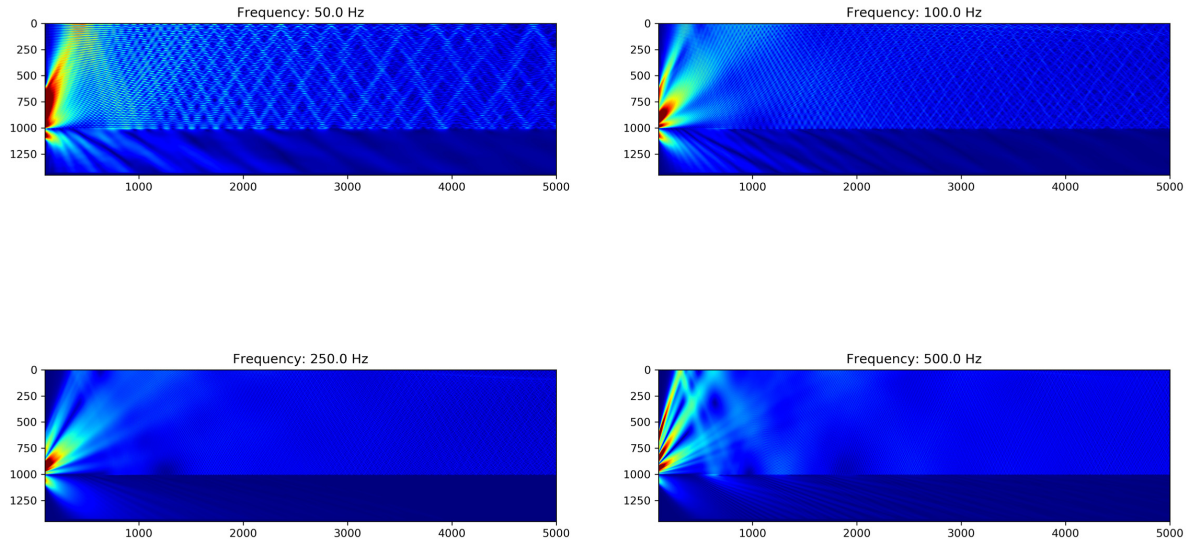

Fig. 4. Acoustic maps of pressure levels calculated with the parabolic equation method for a source above a hole with an fluid sediment

Since we can, with the spectral element method, handle a source situated inside an elastic sediment, it will be interesting to incorpate it into a full-wave simulation to evaluate the effect of such a source of noise.

B. Coupling with a ray tracing software

The SEMANTIC-TS company has developped a software called RAYSON[1] which can generate pressure level maps by solving the Eikonal equation using ray tracing in complex environments. This system of differential equations is solved numerically using a 4th order Runge-Kutta scheme for the range marching [8]. This software has been implemented in C++. RAYSON is able to take into account various realistic environments for propagation loss calculations:

- Range independent medium: horizontally homogeneous
- Range dependent medium: 2D description (range, depth) of sound speed profiles.
- Bottom profile and nature type dependent on range. Type of bottom is chosen among: sediments, sand, mud, rock, semi-inifinite fluid bottom, multi-layered fluid bottom over a semi-infinite elastic medium.

RAYSON also handles source directivity. This is this feature that we will use to perform the coupling with the spectral-element method. The directivity pattern calculated with the

[1]A demo version with documentation of the RAYSON software is available at https://semantic-ts.fr/

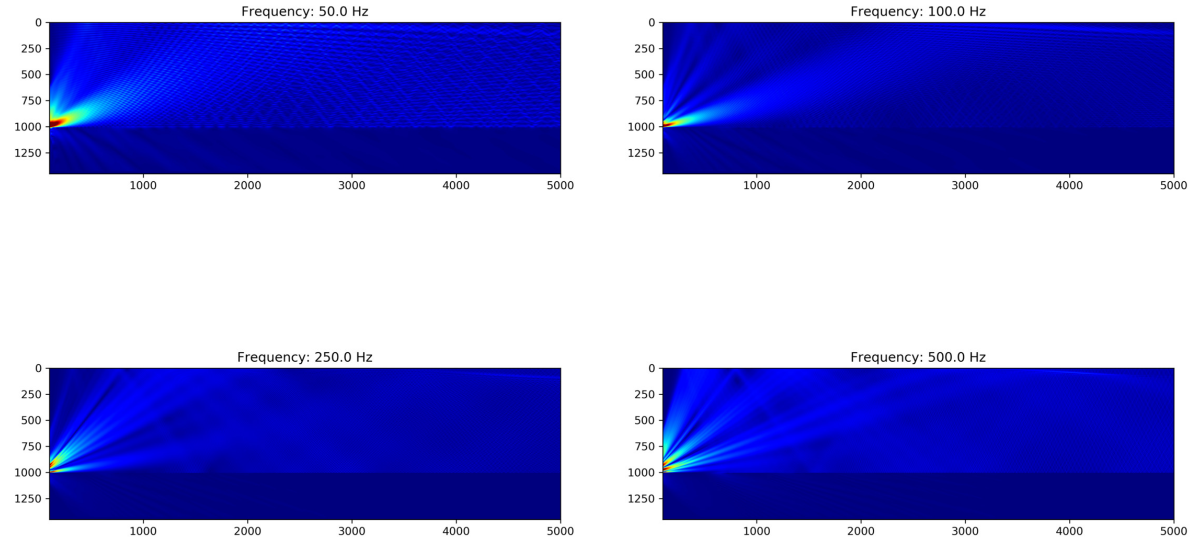

Fig. 5. Acoustic maps of pressure levels calculated with the parabolic equation method for a source above a flat interface with an elastic sediment for different frequencies

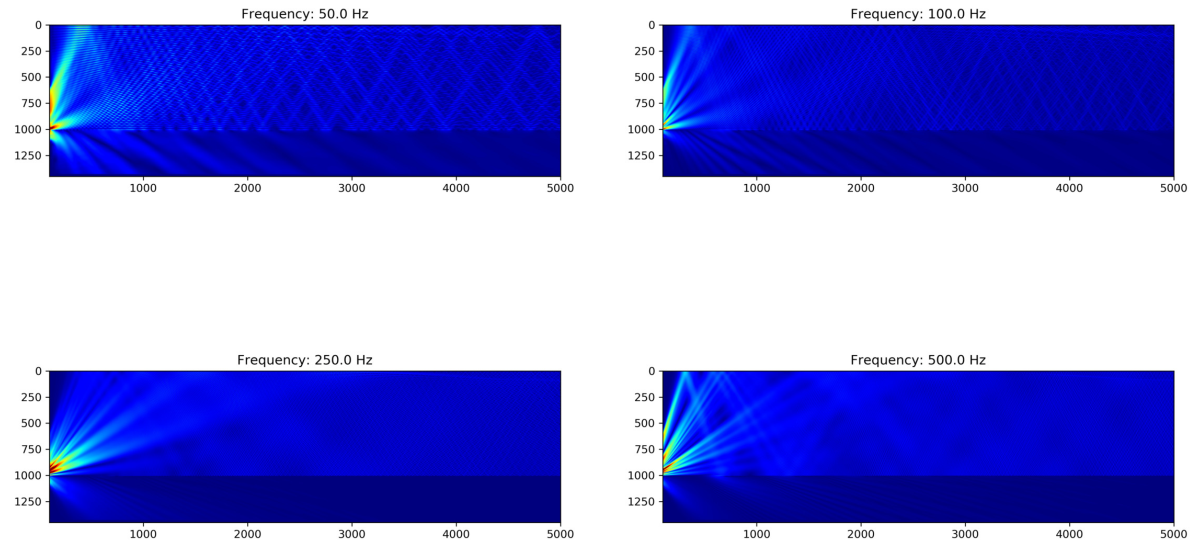

Fig. 6. Acoustic maps of pressure levels calculated with the parabolic equation method for a source above a hole with an elastic sediment for different frequencies

spectral element method as indicated in section III is generated for the different frequencies we chose to consider. hen, the calculations of propagation loss maps are made through a systematic insonification from the source using a regular grid in range and depth.

For a fluid sediment bottom, results provided by the ray tracing method have a similar shape as the ones obtained with the parabolic equation method. The presence of a hole has the same influence on the sound field. The findings are the same for an elastic bottom.

Altough similar, the results are slightly different. Further investigations are currently ongoing, more specifically on the level normalization between the two models, in order to get a better fit.

V. Conclusions

We have presented a method for the coupling of a time-domain full-wave numerical method with a ray tracing method and a parabolic equation method. The preliminary results, we obtain, are very promising. We were able to perform the coupling for both methods. In the future, we will consider other applications with more complex configurations where the

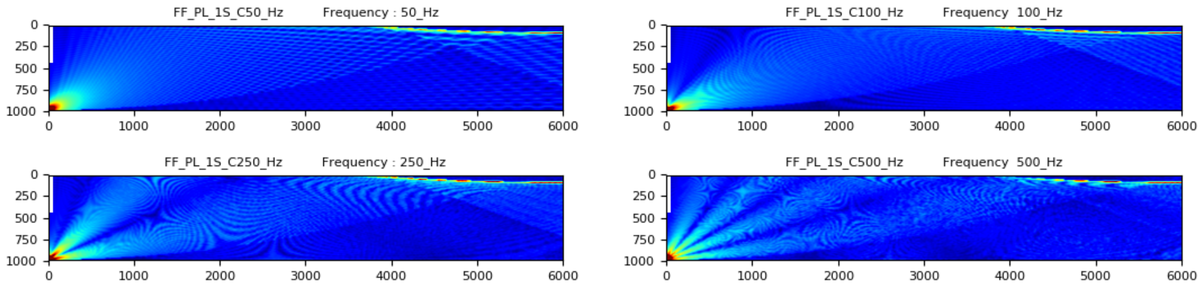

Fig. 7. Acoustic maps of pressure levels calculated with a ray tracing method for a source above a flat interface with an fluid sediment

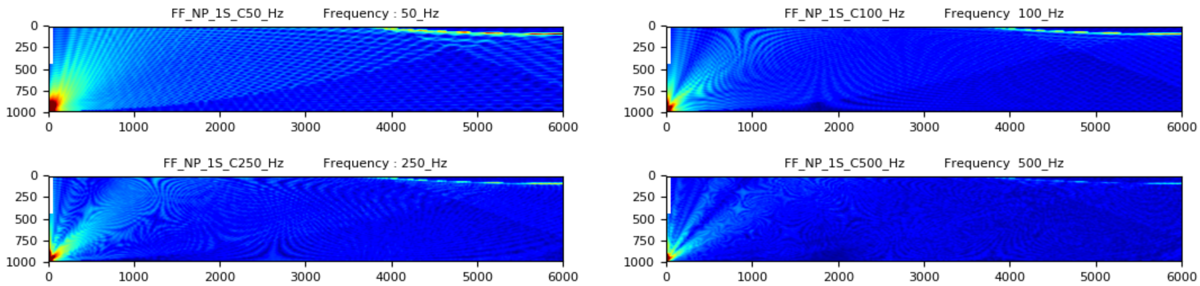

Fig. 8. Acoustic maps of pressure levels calculated with a ray tracing method for a source above a hole with an fluid sediment

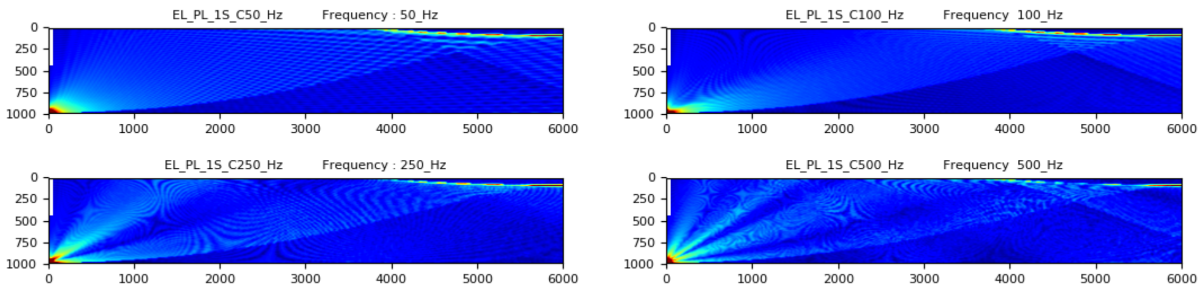

Fig. 9. Acoustic maps of pressure levels calculated with a ray tracing method for a source above a flat interface with an elastic sediment for different frequencies

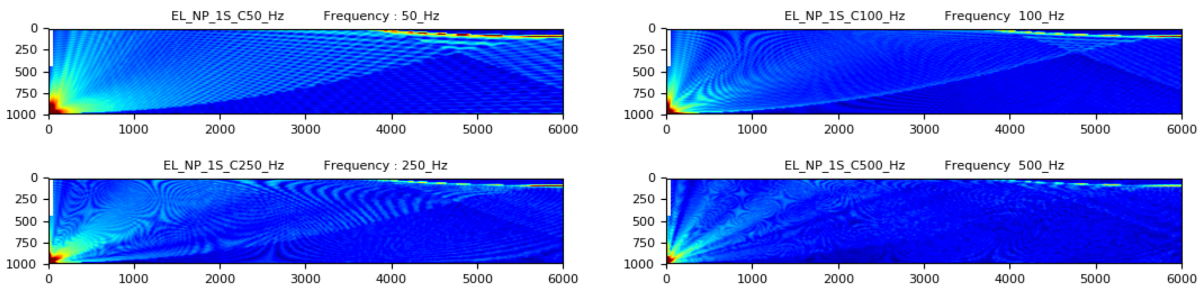

Fig. 10. Acoustic maps of pressure levels calculated with a ray tracing method for a source above a hole with an elastic sediment for different frequencies

presented technique could be used for both deep and shallow water propagation.

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