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DIRECTIVITY OF SHIP PROPELLER NOISE RADIATION

JENSSEN Arne J. K.

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8) ABSTRACT

The directivity of the sound radiation from the propeller area of a ship is studied. The approach has been to measure a scale model of a ship and model the directivity by use of a numerical method called the Boundary Element Method (BEM).
It is shown that BEM is able to predict the measurements of the scale model, and that the shape of the ship hull has an influence of the directivity of the sound from the propeller area.

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DIRECTIVITY OF SHIP PROPELLER NOISE RADIATION

1 INTRODUCTION

1.1 Statement of problem

Noise radiation from ship is influenced by many factors. For mine sweeping it is desirable to have general knowledge about the radiation directivity of noise from a ship. This is an significant factor for comparing the similarity of a target ship and a mine sweep. And is thus valuable for a mine sweep efficiency calculation.

The radiation pattern is characterized by the directivity of the noise for different frequencies.

Here the noise from the propeller area have been investigated

1.2 Background information

Noise from ships have been studied earlier.

Arveson have measured a merchant ship (1). Three major noise generation mechanism were identified to be (1) the auxiliary engine at low speeds, (2) main propulsion engine at higher speeds, and (3) the propeller. The propeller produces high level single tones at the frequency of the blade rate and higher harmonics of that. This is a result of the blade hitting bubbles at the wake of the ship. The frequency of that is typically at around 10 Hz. In addition the bubbles from the propeller also makes high frequency broadband noise which has a significant sound level.

Kinns and Bloor (2) have used BEM (Boundary Element Method) to model hull vibration excitation due to monopole and dipole propeller sources. They found that

- Once the significant cavitation has developed on the propeller blades, a simple stationary monopole, located at the position of the maximum cavitation volume, represents the dominant source term in many cases of practical interest
- The effect of non-cavitating source on vibration are almost negligible at 2bpf or higher mupltiples of bpf, so far as surface ship hull excitation is concerned.
- The sea surface can be modeled as a pressure release surface at frequencies more than a few Hz for typical propeller dimensions and immersion.
- A complex, but compact, cavitation region can be modeled as a single stationary monopole source, so far as determination of pressures away from the immediate vincinity of the propeller are concerned

- A much more rapid convergence of the computation can be obtained by increasing the concentration of elements near the source itself to reflect the expected fall in hull pressure with increasing distance from the source
- Results for floating bodies are derived by replacing the Green function for a monopole or dipole in free space by functions which include the influence of a flat free surface. In effect this represents an extension of the image techniques developed by Vorus for an incompressible fluid, where the rigid surface of the hull is reflected in the notional flat surface of the sea and where sources below the sea surface are preproduces with opposite sign above the sea surface.

1.3 Aim

The aim of this investigation is to measure the directivity of a sound source at the propeller position of a simplified hull model. The measurements is done in an anechoic chamber.

Secondly the measurements should be modeled. Both the boundary element method (BEM) and the finite element method (FEM) are candidates for that. Both have been applied but focus have been on BEM.

2 THEORY AND REVIEW

2.1 BEM

The Boundary Element Method (BEM) is used here to numerically model the radiation of noise from the ship propeller. The technique is widespread in acoustics and described in e.g. (5) and (4),

In short the method is based on the Helmholtz equation. It is transformed into an integral equation, and by applying the Green's theorem the volume integral is converted to a surface integral. This surface integral is solved numerically by discretizing the surfaces into a set of boundary elements. The boundary element method then finds the pressure of all the boundary elements. Secondly with the the pressure known on all elements of the boundary, the resulting sound field can be computed at any position, a so called *fieldpoint*, either inside or outside the boundary.

2.1.1 The integral equation

In acoustics the BEM technique is suitable to model external problems like sound radiation and scattering from bodies and internal problems like sound propagation inside a structure.

Unlike the finite element method (FEM), where the whole volume is discretized with elements, only the surface of the structures is discretized in BEM.

The advantages of BEM are:

- Only the surface or boundary of the object needs to be discretized into elements
- No formulation problem for infinite domain
- Very suitable for radiation and scattering problems

And drawbacks:

- The method leads to full matrices that can lead to high computation costs.
- External problems might fail to provide unique solution at eigen frequencies

2.1.2 BEM variants

The boundary element method in acoustics is based on expressing the acoustic variables (pressure, velocity, intensity) within the acoustic volume as a surface integral over the boundary of the acoustic domain. The surface integral contains the primary variables of the formulation, the Green's function, and derivatives of the Green's function. There are two distinct boundary formulations available, the *direct* and the *indirect*. The difference between them stems from the definition of primary variables. The acoustic pressure and the acoustic velocity constitute the primary variables in the DBEM. The difference in pressure and difference in the normal gradient of the pressure across the boundary element model constitute the primary variables in the IBEM.

2.1.3 The CHIEF method

One way to overcome the non-uniqueness difficulty is to use the CHIEF (Combined Helmholtz Integral Equation Formulation) method proposed by Schenck (3). In the CHIEF method additional points are located inside the structure of an external scattering problem, and those so called CHIEF points enforce zero pressure condition. This makes the matrix system overdetermined and the resulting solution become numerically stable. If the CHIEF point are positioned on any interior nodal surface, it does not work since the pressure is already zero there. These nodal surfaces are usually not known in advance of the solution. Therefore the best strategy is to scatter a cloud of randomly positioned CHIEF points inside the structure, and since the number of nodal surfaces increases with increasing frequency, the number of CHIEF points should also increase.

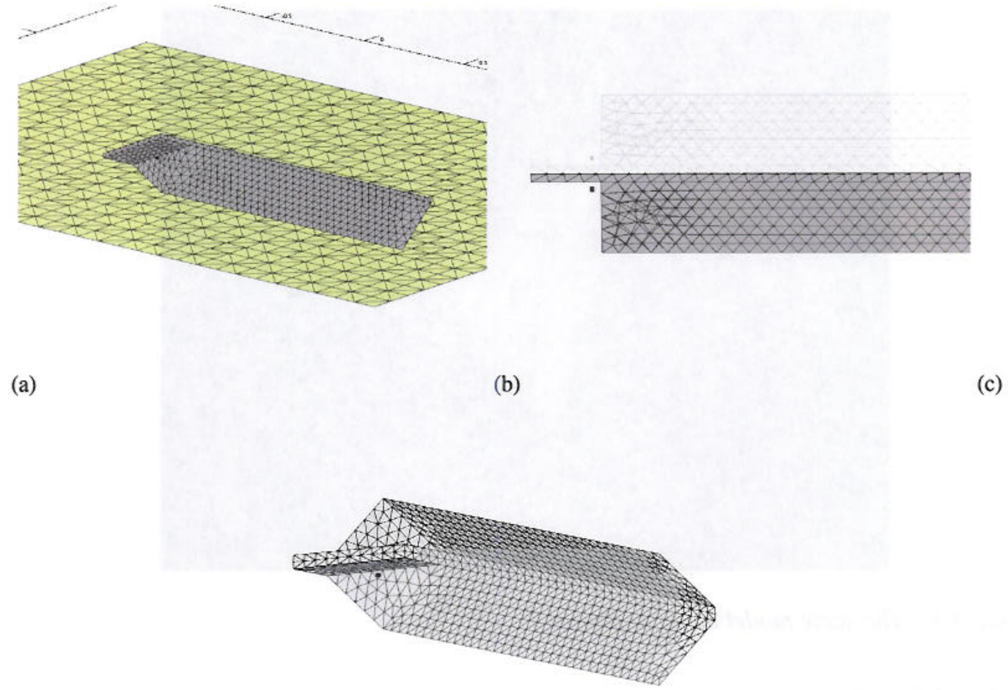
2.2 Modeling of the hull and propeller

Sound radiation from a ship propeller can be modeled in three different ways by use of BEM. One direct way is to model the propeller, the part of hull that is submerged in water and the water surface as illustrated in Figure 2.1(a). The water surface must be discretized in to elements at a significant distance. This method requires a lot of elements which results in heavy computational costs.

The second possibility in modeling is to take advantage of that the sea surface can be treated as an infinite reflecting plane. This can be done in two ways. First one can modify the Green's function by adding a term that represents the reflecting reflecting surface (see Figure 2.1(b). The Greens function would then be of the form

$$\Psi_H = \frac{e^{-ikr}}{4\pi r} + R_H \frac{e^{-ikr'}}{4\pi r'}, \tag{2.1}$$

where r' is the distance to the image source, and R_H is the reflection coefficient of the half-space. This approach requires that the computer implementation of the model has that possibility or that one can access the computer code and change the Green's function. For the software used here it was not easy to change the Green's function. Therefore it was not done. The third way is to use the image source technique. The reflecting surface is replaced with a virtual image source. For the case here, the virtual source of the propeller is phase shifted because of the soft boundary condition of the water surface. The hull is reflected and a double hull is obtained. This is illustrated in Figure 2.1(c). The advantage to this approach is that one can use existing BEM software without changing the Green's function, the number of boundary elements is reduced since the surface of the reflected hull is much smaller than the water surface that needs to be discretized, and finally one can make an analogous physical scale model of a double hull to be measured in air.



(a) (b) (c)

Figure 2.1 Different ways to discretize the boundary of a hull in water a) The hull and some of the water surface is made into elements, b) Only the hull is discretized and the water surface is replaced a modified Green's for a reflecting surface c) A double hull is discretized and can be used directly with existing BEM software

3 MATERIALS AND METHODS

The investigation was done in two parts. First an experimental part where a scale model of a ship hull was measured in an anechoic chamber. The second part was numerical modeling of the measurements.

3.1 Scale model measurements

The experimental part was performed by IASTE [1] student Woitek Bijok from Poland which resided at NTNU in september 2004.

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[1] International Association for the Exchange of Students for Technical Experience

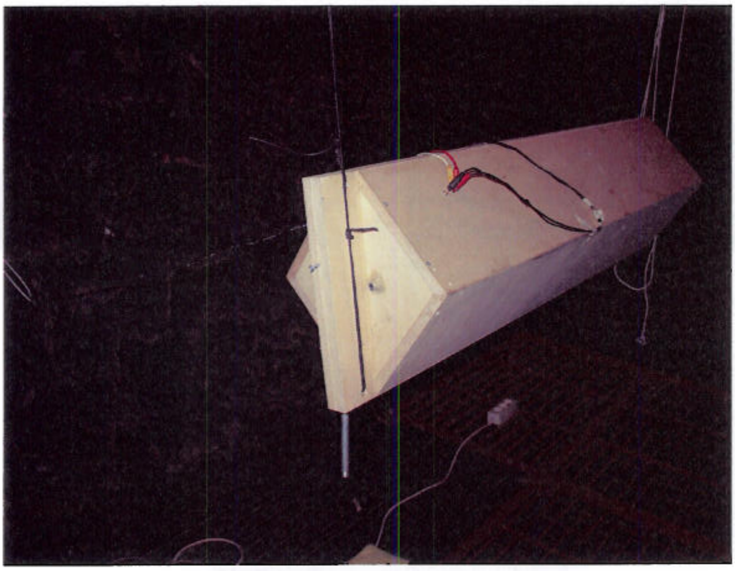

Figure 3.1 The scale model made in plywood

3.1.1 Materials

Loudspeakers Loudspeakers from Chunilon Corporation model No: PC77DU60-02FP with the parameters as given in Table 3.1.1.

Normal impedance	8 OHM
Nominal power	10 W
Maximum power	20 W
Resonance frequency	120 Hz
Rated freq range	?? - 12000 Hz
Sound Pressure Level	89 dB/W

Table 3.1 Parameters of the Chunilon loudspeaker.

Signal generator A Bruel and Kjær beat frequency generator was used. It generated single tone signal. I was also used to control the rotary table that the microphone beam was attached to.

Scale model The scale model was build with plywood of 13 mm thickness with the following dimensions: length 1220 mm, width 346 mm, height 306 mm. It was shaped like two hulls (see Figure 3.1)

In each half of the hull a loud speaker was placed. It was insulated from the hull by embedding it in mineral wool. A funnel was connected to a steel tube penetrating the hull at the stern position, and the sound from the loud speakers could radiate out through the tube in order to simulate propeller sound.

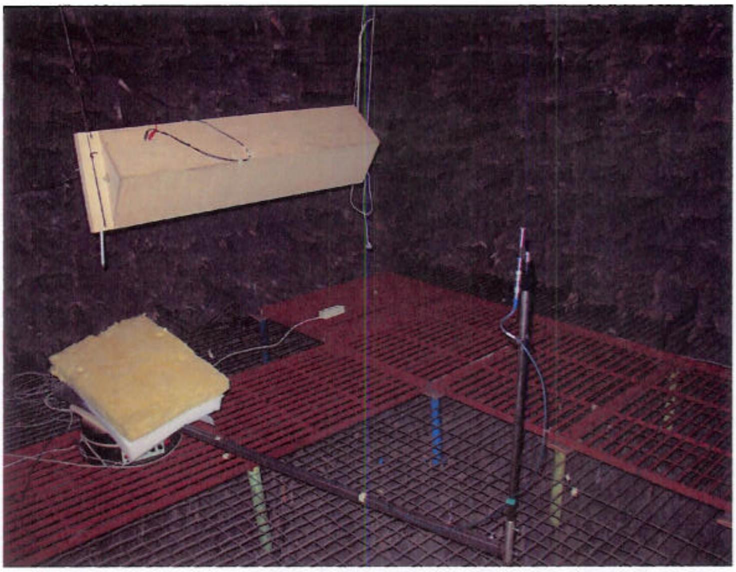

Figure 3.2 The scale model is hung in anechoic chamber and a microphone attached to a rotary table sweeps a semicircle

3.2 Measurements

The scale model was hung in ropes from the ceiling in an anechoic chamber. A pulley system allowed the scale model hull to swivel around its length axis. A microphone attached to a rotary table swept a semicircle of radius 1.6 m around the hull with its center of rotation aligned with the propeller (see Figure 3.2). The curves that the microphone measured along are illustrated in Figure 3.3.

Each recording lasted around 41 seconds. The microphone started right in front of the bow and swept the half circle and ended up behind the stern. Single frequency tones were played through the loudspeakers. The two loudspeakers were phase reversed in relation to each other in order to simulate a infinite pressure release water surface. The frequencies used ranged from 250 to 4000 Hz in 250 Hz spacing. The hull was measured at tilt aspect angles from 0 to 90 degrees in steps of 5 degrees. Two series of the recordings were made. The first series had a hull with a 150 mm long stern, and before the second series the stern was halved to 75 mm length.

The recorded sound was sampled directly on a PC and recoded into wav-files.

3.3 Numerical modeling

The sound radiation from the propeller of double hull experiment was modeled numerically by use of BEM. The software used and modeling procedure is described in the following sections.

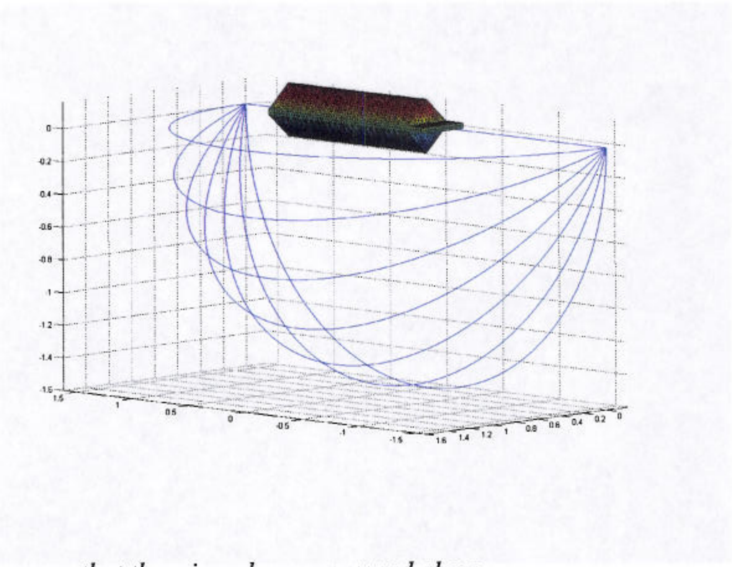

Figure 3.3 The curves that the microphone measured along

3.3.1 Software

Helm3D is an implementation of the direct boundary element method. The source code was included with the book by Wu (5). It was modified a little to allow for bigger matrices so that more elements could be used, and the interface was changed. The output was split into several files to make it easier to parse in matlab. It was compiled with Compaq Visual Fortran for Microsoft Visual Studio 6.0.

IVBEM - Indirect Variational Boundary Element Method is an implementation of the indirect BEM by N Vlahopoulos. The source code was also from the book by Wu (5). The FORTRAN code was changed to allow for bigger matrices. The program required the user to input the parameters frequency (f), medium density (ρ), and sound speed (c) interactively. This was very inconvenient for running the model in a script. Therefore the required parameters was given into the model by adding an input file `params`. This was done by adding the following lines to the code

```
open (unit=21, file='params', status='UNKNOWN')
...
 read (21,*) f, rho, csound
```

The source code was compiled with GNU G77 compiler.

I-DEAS [2] is a CAD software that was used to make a 3D model of the ship hull and generate boundary meshes for the BEM models. The software is very powerful but requires the user to follow a rigid and counterintuitive procedure. It has a very limited undo possibility which makes the software inconvenient to use.

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[2] http://www.eds.com/products/plm/ideas/

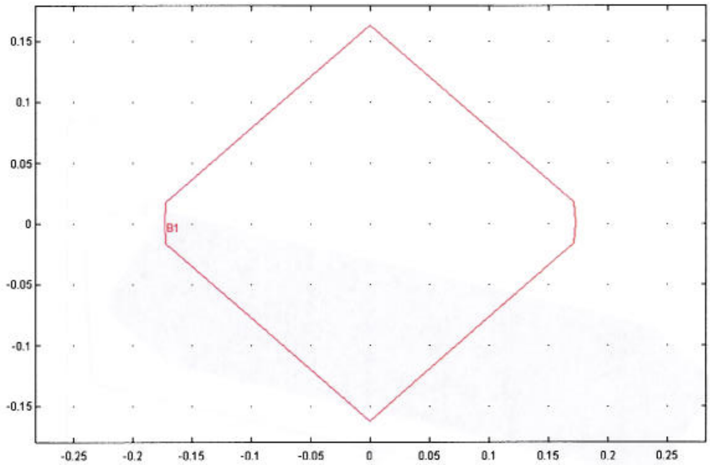


Figure 3.4 *The cross section of the hull. Note the small widening at the waterline to enforce element boundaries*

Meshing software The Internet was searched for free meshing software, but it was difficult to find. Most of the free meshing software made only finite element meshes, which cannot be applied on the boundary element method because boundary meshes was needed. The only software found to be usable was I-DEAS.

Matlab was used to generate input files to the BEM model, execute the computations and visualize the results.

3.3.2 Modeling procedure

Making the mesh

1. Make the rear view cross-section in the y-z plane. A polygon as shown in Figure 3.4 is made. Note that extra vertices are added at the waterline to enforce splitting of the elements along that line.
2. The cross section is extruded 1.4 m in forward direction and 0.15 m in backward direction as shown in Figure 3.5.
3. In the side-view, or the z-x plane, a polygon with the shape shown in Figure 3.6(a) is made to resemble the profile of the stern. The polygon is extruded to a solid that is used to cut out the stern as seen in Figure 3.6(b)
4. In the side-view a similar shape was made to cut out the front part of the ship. Two versions were made. One with a bow and one without a bow. Here the shape of the one without the bow is shown.
5. A boundary *mesh was generated* by the software. The user can specify the average size of the elements. The values between 12 and 30 mm were used. An example of a finished mesh of the hull is shown in Figure 3.7.

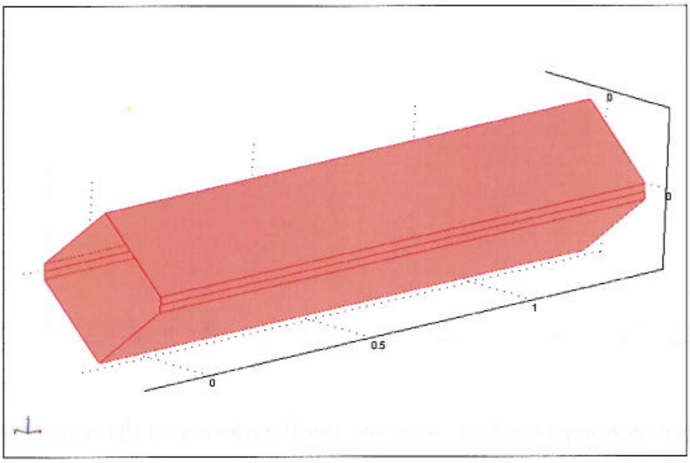
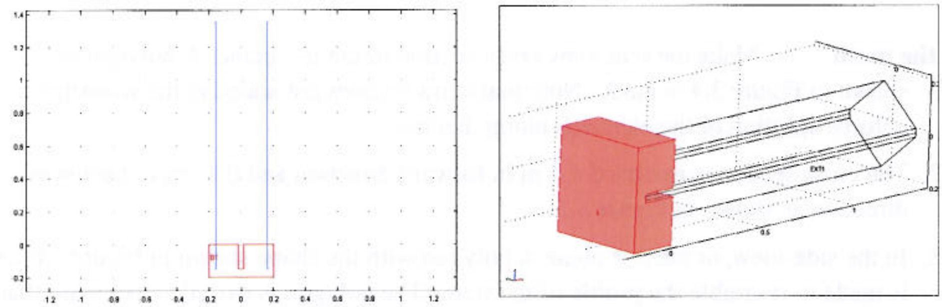


Figure 3.5 The cross section is extruded



(a) (b)

Figure 3.6 (a) The shape of the object used to cut the stern, (b)the extruded object

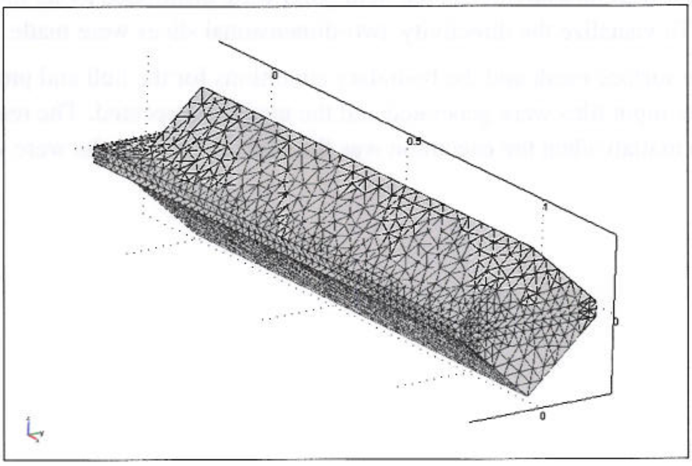


Figure 3.7 The meshed hull

	Helm3d			IVBEM	
	CA	CB	CC	v_n	dp
Hull	0	1	0	0	0
Upper propeller	0	1	1	1	0
Lower propeller	0	1	-1	-1	0

Table 3.2 Boundary conditions for Helm3D

The mesh of the propellers was either be made with the same software, then they took the shape of small cylinders, or optionally they were generated in matlab with the sphere function.

Running BEM software The input to the BEM software are the (1) *mesh,* (2) *boundary conditions*, (3) *fieldpoints*, and *parameters* like frequency, soundspeed and mediumdensity. The fieldpoints are the positions where the resulting sound field is to be computed

To run the BEM model, the mesh was imported into Matlab. The boundary conditions for the elements were set. In Helm3d the boundary conditions are given with the parameters CA, CB, and CC, according to the relationship

$$(CA)p + (CB)v_n = CC, \tag{3.1}$$

, and in IVBEM the boundary conditions are specified with velocities and pressure difference. The boundary condition used are summarized in Table 3.3.2.

Since the source strength of the loudspeaker was not measured during the experiment, the velocities of the propeller elements was set to unity. Therefore the result from the BEM model will have to be scaled to fit to the measured data.

Depending on what type of result desired, different fieldpoint configurations were used. For comparison with measurements, the field point were positioned along the lines of the microphone. To visualize the directivity, two-dimensional slices were made.

Thus from the surface mesh and the boundary conditions for the hull and propellers, and the field points input files were generated and the model is executed. The result was imported into matlab when the execution was finished, and the results were visualized.

4 RESULTS

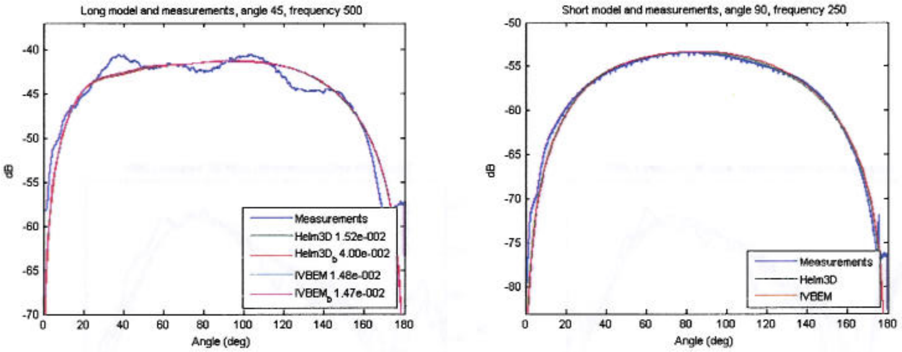
The results from the measurements and modeling are presented here.

The results are presented in several ways. Line plots are for comparison of measurements and models, and collective plots of the measurements are mapped on to a spherical surface to get an impression of the overall directivity of the propeller noise. Results from the BEM models alone are presented as image plots where the the field points are located on a two dimensional surface. These plots make it easier to get an impression of the directivity.

4.1 BEM model and measurements

The two BEM program, Helm3D and IVBEM, was used to model the sound radiation form the scale model. The results of that are plotted together with the measurements. For brevity only a few results are presented here see figure 4.1, figure 4.2, and figure 4.3. The results are presented both for the long and short stern of the hull. For the long stern two different meshes were used. Mesh *a* had 3690 elements and mesh *b* had 5596 elements, and the mesh for the short stern model had 5462 elements.

Since the particle velocity was not measured, the velocity of the boundary elements were set to unity. Therefore the results of the BEM models had to be scaled to fit the measurements. This was done by computing a scaling factor from the mean values. The mean squared error



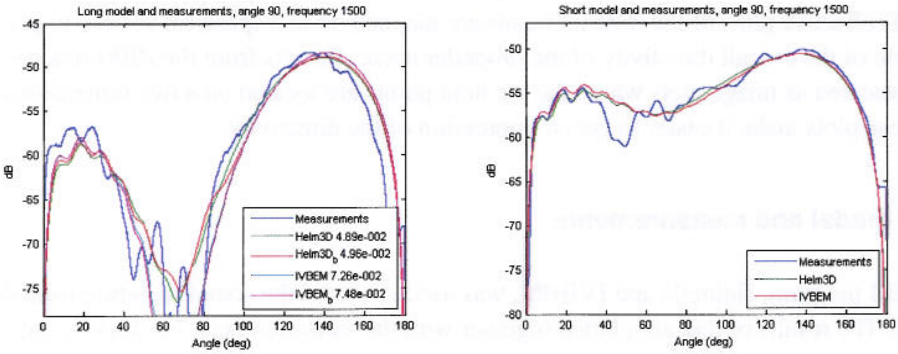
(a) (b)

Figure 4.1 250 Hz 90 degrees (a) Long hull (b) Short hull

For more results see page 30.

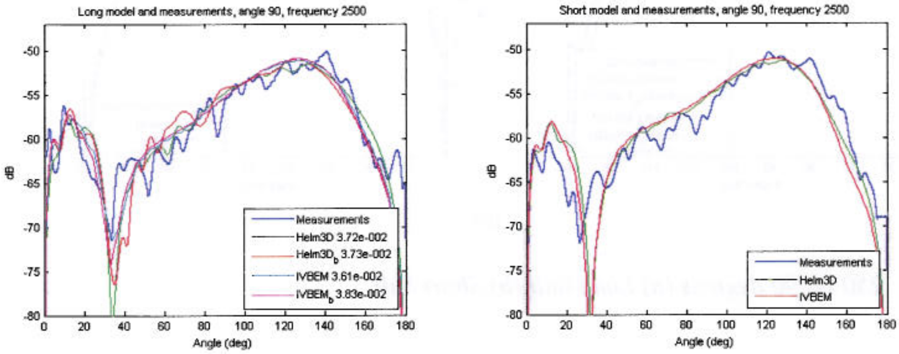
4.2 Spherical plots of measurements

The measurement of the scale model covered a quarter of a sphere around the hull. All measurements for one frequency are combined to make spherical plot (Figure4.4). This can be helpful to get an impression of the directivity of the radiated sound from the propeller area.



(a) (b)

Figure 4.2 1500 Hz 90 degrees (a) Long hull (b) Short hull



(a) (b)

Figure 4.3 2000 Hz 90 degrees (a) Long hull (b) Short hull

A blue line is drawn on the plots where the hull was located, and a star denote the position of the propellers.

One can see from the figures that at low frequencies the sound have dipole characteristics like that of a monopole close to a reflecting surface. At higher frequencies the hull appears to block the sound from radiating forward, and one can see that most of the sound is radiating backwards.

4.3 Vertical slices

Plots of vertical slices are made with the BEM models to visualize the directivity of the radiation how it would look straight below the ship. An example of such plots are shown for different frequencies in Figure 4.5

At low frequency one can see that the propeller radiates almost omni-directionally, the wavelength at 500 Hz is around 1.4 m, which is much longer that the width of the hull and slightly longer than the length of the hull. The noise seem to be little influenced by the presence of the hull.

At higher frequencies the radiation pattern changes. From the plots one can see that most of the intensity is radiated in the 7-8 o'clock sector. It it seems like the sound are obstructed by the hull and therefor cannot radiate in the forward direction. This means that the ship will have passed before the highest sound intensity for higher frequencies have been perceived at a point at the sea bottom.

For more results see page 30.

4.4 Horizontal slices

A horizontal plane of detectors are also made to give an impression of how the directivity spread out on the bottom. This can give an indication of how bottom mines might perceive a ship passing over. But one must be aware that the bottom is not taken into consideration during simulation, the bottom will have a strong influence on the sound, so those results presented here are just an indication of how the sound might radiate if the sea was infinite deep.

Result for BEM simulation of low frequency (Figure 4.6(a)) and a high frequency (Figure 4.6(b)) are presented here, and more results are shown in the appendix.

Like in the results for the vertical slices, one can see a omni directional spreading at low frequencies, and at higher frequencies the hull appear to obstruct the noise in forward direction. From these horizontal slices one can also see that more sound is radiated in to the side in the forward direction than directly forward.

For more results see p. 30.

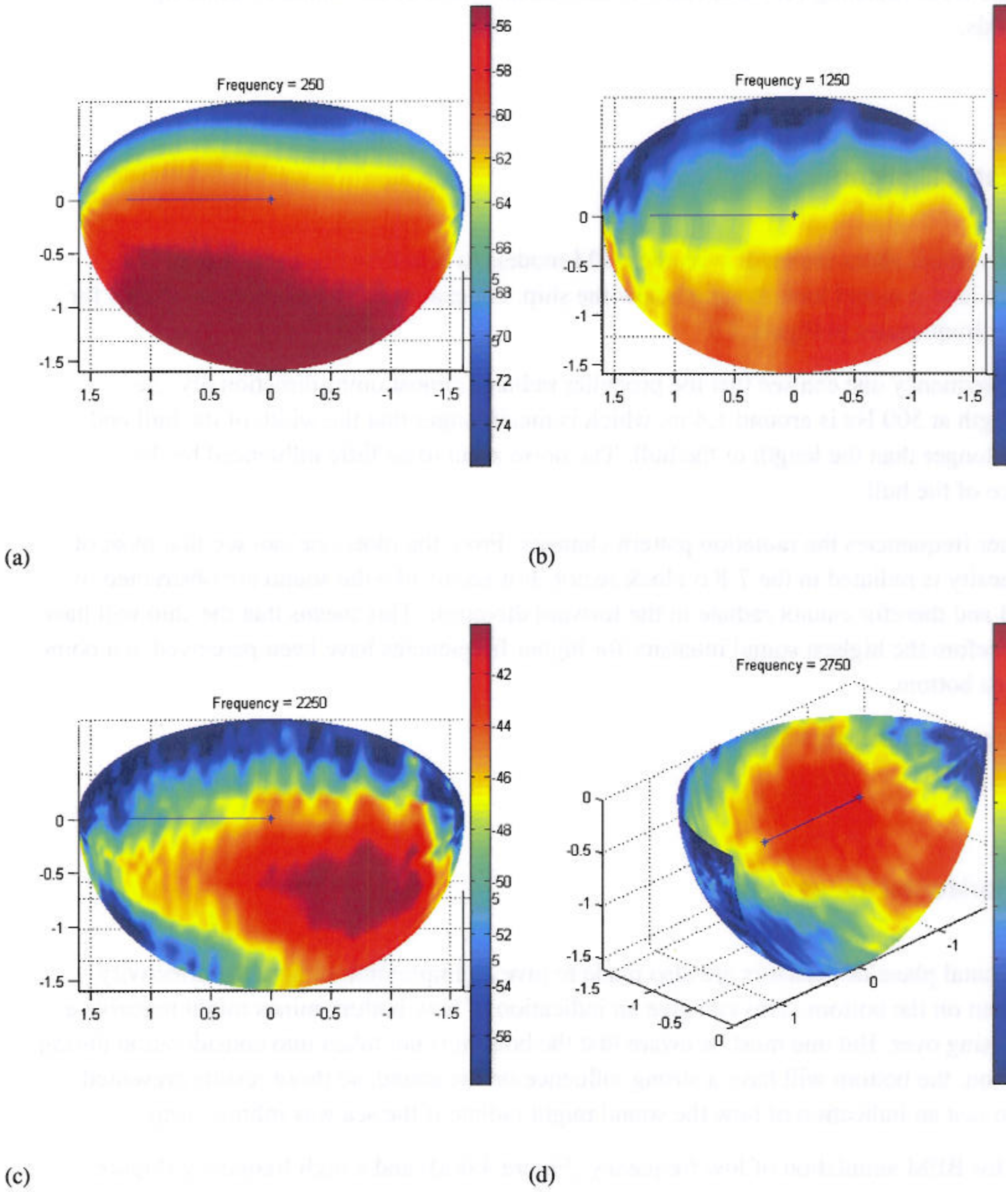
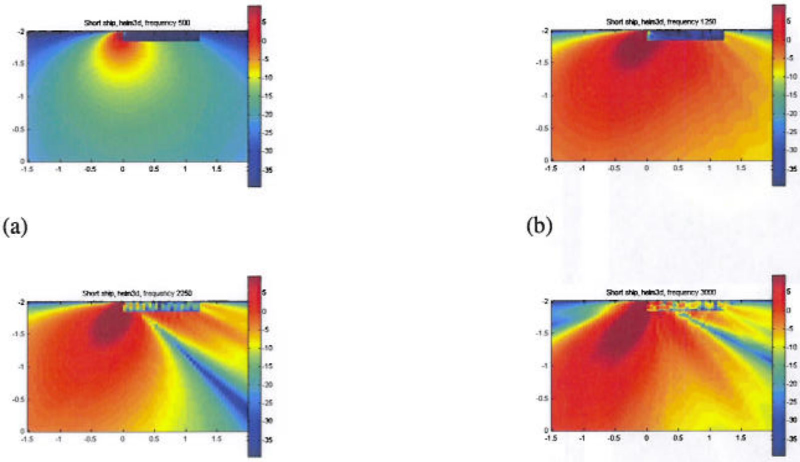


Figure 4.4 Measurements collected



(a) (b) (c) (d)

Figure 4.5 Vertical slice modeled with Helm3d a) 500 Hz, b) 1250 Hz, c) 2250 Hz, and d) 3000 Hz

4.5 Meshes

A rule of thumb for applying the BEM is that there should be at least around 10 elements per wavelength. Therefore at higher frequencies a finer mesh with more elements is needed. This also means that bigger matrices have to be treated and thus more requirements on computing time.

The two BEM programs used here had a maximum number of elements of 9999 and 5700 respectively for Helm3d and IVBEM. Therefore the meshes that were used had around 5000 elements. For frequencies between 250 and 4000 Hz this gives number of elements per wavelength between 44 and 2. See table 4.5 for more details. It is evident that the meshes used here are too coarse for frequencies above 2500 Hz.

For the hull with the long stern, multiple meshes were made with slightly different number of elements. Mesh a had 3690 elements and mesh b had 5596 elements. Those were used for the two BEM programs Helm3D and IVBEM. It appeared that Helm3D was very sensitive to the mesh for higher frequencies, whereas IVBEM produced very similar result regardless of the mesh used.

4.6 Frequency response

The frequency response for Helm3D was computed for a field-point positioned straight under the propeller. Different number of CHIEF points was used and the results are shown in Figure (4.7). One can see that for 0 CHIEF points the frequency response shows that the model is very sensitive to some frequencies. The first peak at 1050 Hz corresponds with one wavelength distance across the height of the hull. This undesierable effect of standing waves inside the

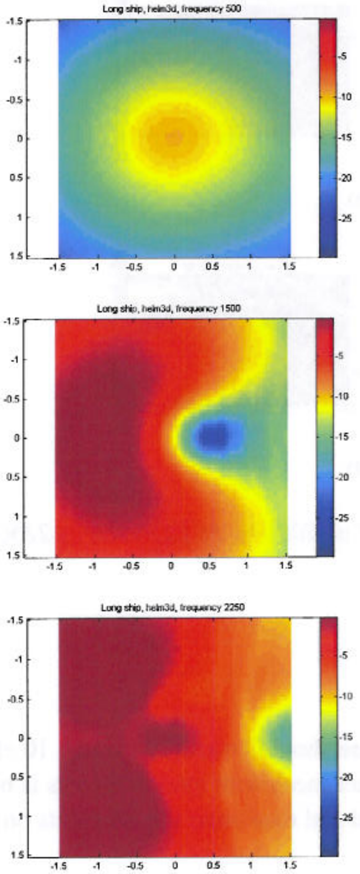


Figure 4.6 Horizontal slices at depth 1.2 m a) 500 Hz, b) 1500 Hz and c) 2250 Hz

Frequency	Elements per λ	Frequency	Elements per λ
250	44.5	2250	4.9
500	22.3	2500	4.5
750	14.8	2750	4.0
1000	11.1	3000	3.7
1250	8.9	3250	3.4
1500	7.4	3500	3.2
1750	6.4	3750	3.0
2000	5.6	4000	2.8

Table 4.1 Elements per wavelength for different frequencies for a typical mesh of around 5000 elements. The rule of thumb is that there should be around 6-10 elements per wavelength

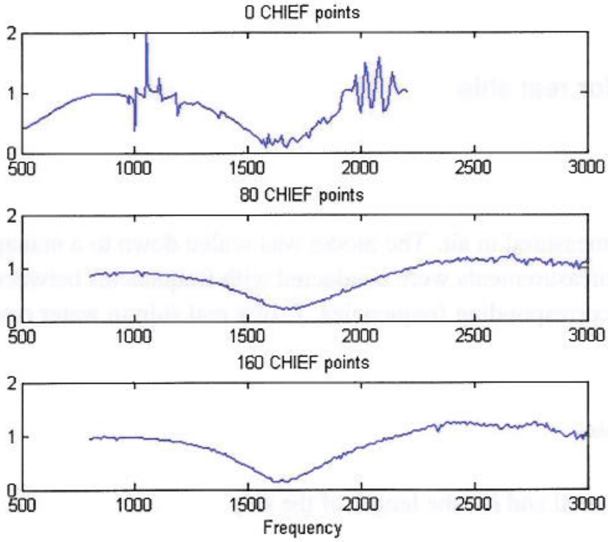


Figure 4.7 Frequency response for a point for different number of CHIEF points

structure is removed when adding more CHIEF points as seen in the two last plots in Figure (4.7). One can see only a minor difference between 80 and 160 CHIEF points for the highest frequencies. The other results shown in this report was computed with 80 CHIEF points.

5 DISCUSSION

5.1 Implications for real ship

5.1.1 Frequencies

The scale model was measured in air. The model was scaled down to a manageable size with a length of 1.2 m. The measurements were conducted with frequencies between 250 and 4000 Hz in air. To find the corresponding frequencies, f, of a real ship in water one can use the expression

$$f_{\mathrm{ship}} = \frac{c_{\mathrm{water}}}{c_{\mathrm{air}}} \frac{l_{\mathrm{model}}}{l_{\mathrm{ship}}} f_{\mathrm{model}}, \tag{5.1}$$

where c is the sound speed and l is the length of the ship.

Thus the frequencies for a ship of length 70 m would be as given in table 5.1.1.

Model Frequency	Ship Frequency	Model Frequency	Ship Frequency
250	18.9	2250	170
500	37.8	2500	189
750	56.7	2750	207
1000	75.6	3000	226
1250	95.5	3250	254
1500	113	3500	264
1750	132	3750	283
2000	151	4000	303

Table 5.1 Frequencies used in model measurements and simulation and the corresponding frequencies for real ship of 70m length in water

5.1.2 Simplifications

A lot of simplifications were done. First the hull shape is very simplified to be easy to craft in wood and also easy to make numerical models of. Therefore the hull had no curved surfaces as a real ship would have, and the bow was flat. This is sensible for the comparison of the measurements and numerical model results. But one should be careful about making conclusions for a real ship.

Secondly the sound source are loudspeakers that radiate out through a tube. This does not resemble a propeller. The dominant propeller sound is when the blade strikes the gas bubbles. This has a monopole characteristics, and the loud speaker-tube system was also measured to have omni directional characteristics at the frequencies used here.

The material of the scale model was plywood which does not resemble steel that ordinary ships usually are made of, but for the sound levels used in the experiment both those materials can acoustically be considered to be rigid.

The simulation and scale model experiment did not take the sea bottom into consideration. In reality the bottom will influence the sound radiation from the ship and create more complicated radiation patterns. But it has an advantage to consider the ship hull separately in order to understand that effect. The bottom can be treated with real ship measurements and also included in a numeric model.

When the model and measurement are in agreement for the anechoic case, the resulting directivity function can be used as an input to a propagation model. Image source techniques and ray tracing are good candidates for such models which easily can be used with directivity.

Sound propagation in water is usually more complicated than the idealized model used here. An important factor that is not taken into consideration is that in the wake of the ship there is a lot of gas bubbles. These cause the sound speed to be locally reduced and means that the sound waves will be refracted. This is most important for the sound that radiates directly backwards into the wake, which is not of most interest anyway.

5.1.3 Noise sources

Although the sound from the propeller is often dominant for a real ship, a substantial amount of noise comes from the main engine, drive shaft and the service generators. That sound radiates out through the ship hull, and is not taken into consideration in the simulations. Therefore the results here can, at best, to some degree say to represent only the component from the propeller.

5.2 Measurements

The measurements were conducted carefully, but they are very prone to misalignment of the setup. It was not easy to align the hull and microphone correctly. This is especially critical when the microphone is right in front of the bow and right behind the stern, because then the microphone is supposed to be equidistant to the two loudspeakers and the sound should ideally be canceled. This is also the case for the 0 degree tilt angle measurement series.

The tilt angle was measured by use of a level and simple triangular goniometer. This was not very accurate, but a deviation of a few degrees are not critical for the results.

In the recordings one could see more than 20 dB lower level at those positions, so one could say that the recordings were as accurate as they could be using the crude equipment and method.

5.2.1 Hull vibrations

The scale model was hung from the ceiling in two strings. Although no visible motion was seen, it can be conceived that the scale model could have been vibrating. But the pendulum movement that would come from the suspension of the model has such a low frequency that the resulting noise will be removed by the bandpass filter.

However if the loud speakers are not completely insulated from the hull, they might cause the hull to vibrate, and the vibration will have the same frequency as the sound that one wants to measure, therefore one cannot filter it away. After the measurements were done it was realized that this type of hull vibration should be measured. That could have been done by placing accelerometers on the hull. But unfortunately that was not done.

5.3 Further work

It has been proposed to use another measurement technique based on the swept sine method. This technique can result in a high signal to noise ratio and is very stable.

5.3.1 Other BEM software

Other BEM software could be used for modeling. The two variants used here was obtained free of charge from a book, and had a purpose of being simple and pedagogical. Thus they don't utilize advanced features and are thus not as powerful and versatile as commercial BEM software. By using commercial software one could get more user friendliness, better results and solve problems for higher frequencies.

5.3.2 Hull vibrations

The other machinery on board the ship and the propeller it self cause the hull to vibrate. Those vibrations radiate noise into the water, and will influence the sound field. Not much is known about this phenomena, but if the hull vibrations are measured, it is conceivable that the resulting sound field in water could be modeled with the same methods as used here.

5.3.3 Equivalent source model

The purpose of this study is to obtain a directivity of propeller noise. For that to serve any purpose it must be put to practical use. The idea is to use the directivity function to make an equivalent source model that can be used in simulations. It is hoped that the complicated ship hull could be replaced by a few monopole and dipole sources that could reproduce the sound field's main characteristics.

6 CONCLUSIONS

This investigation has been two-fold. First an overview and understanding of how propeller noise is radiated into the water was desired, and secondly it was investigated if BEM models could reproduce measurement on a physical scale model.

6.1 directivity

From the measurements one can deduct the directivity of sound from a source located at the propeller position of a simplified scale model hull. At low frequencies the radiation pattern is similar to that of a monopole located close to an reflecting half space. This means that it resembles a dipole and the directivity is omni-directional. But for higher frequencies, the hull seem to influence the directivity of the noise radiation. The sound in forward direction is blocked by the hull. Therefore most of the noise from the propeller area is radiated backwards and to the sides.

6.2 Numerical modeling

The BEM software applied here was Helm3d and IVBEM obtained from (5) turned out to be able to model the measurements quite well at low frequencies and satisfactory at higher frequencies.

One should take into consideration that the software was free of charge and they were designed to pedagogically introduce BEM as simple as possible. Therefore they lack the power and features of commercial software. One advantage with this approach, in addition to be the financial saving, is that the user has more controll of the software behavior and can tailor it to ones need because the source codes are available. This is ideal for the kind of research done here, but for practical use it would be better to have a more user friendly software suite.

References

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(2) Kinns R and Bloor C D (2004): Hull vibrations due to monopole and dipole propeller sources. *J Sound Vibration*, 270:951–980.

(3) Schenck H A (1968): Improved integral formulation for acoustic radiation problem. *J Acoust. Soc. Am.*, 44:41–58.

(4) Wrobel L C (2002): *The Boundary Element Method, volume 1, Applications in Thermo-Fluids and Acoustics*. Wiley.

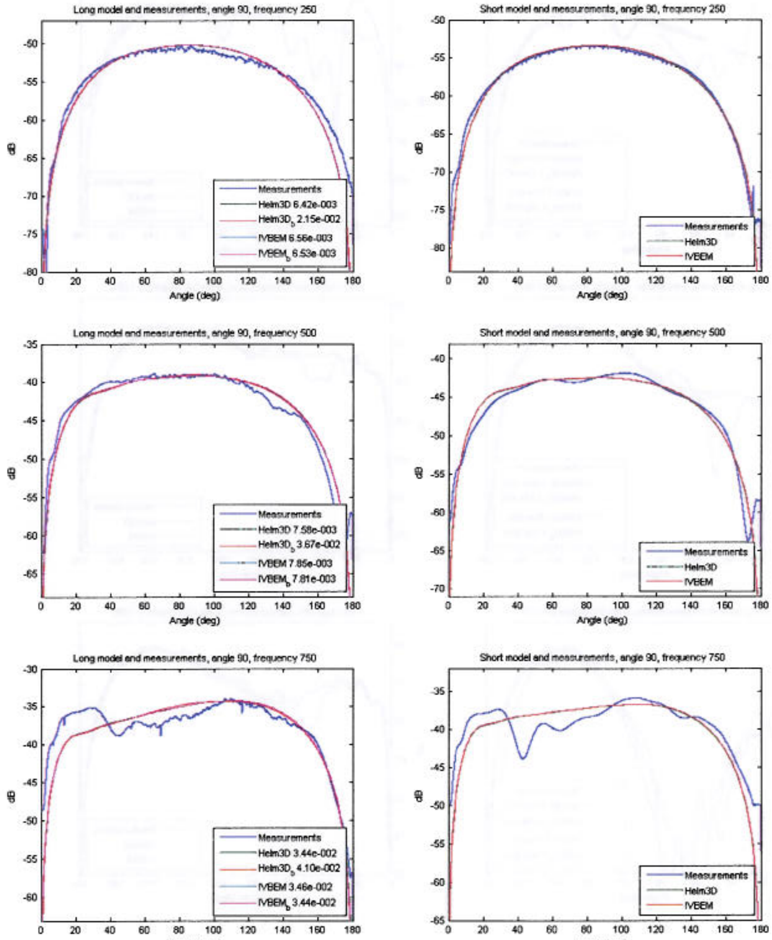
(5) Wu T W, editor (2000): *Boundary Element Acoustics - Fundamentals and Computer Codes*. WIT Press.

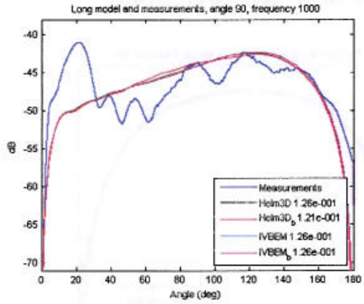
APPENDIX

A OTHER RESULTS

In this section the results have been collected.

(Measurement and model of ship hull, 17-Jun-2005 01:35:08)

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IVBEM 1.26e-001
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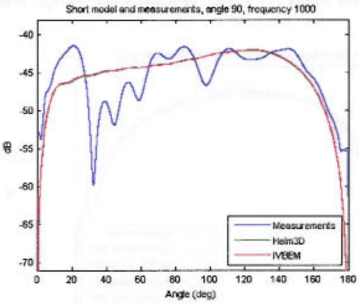
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Measurements
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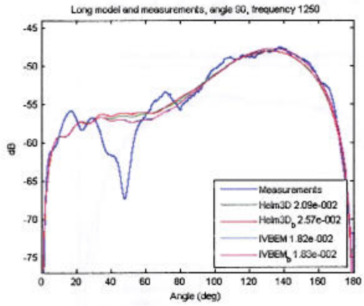
IVBEM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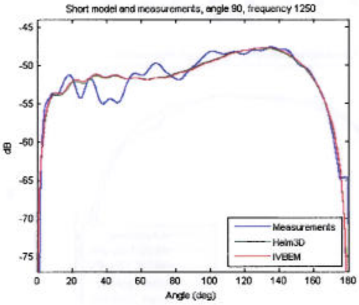
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Angle (deg)
Measurements
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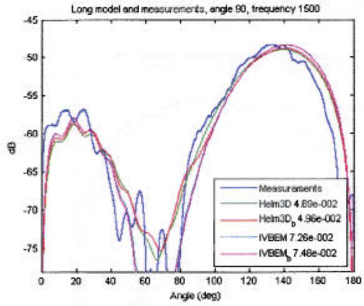
IVBEM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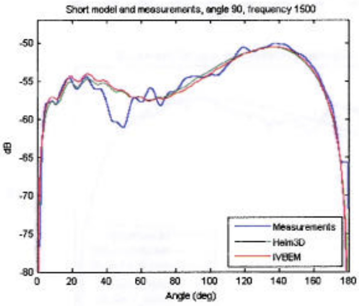
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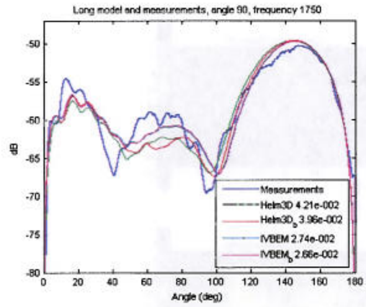
Angle (deg)
Measurements
Helm3D
IVBEM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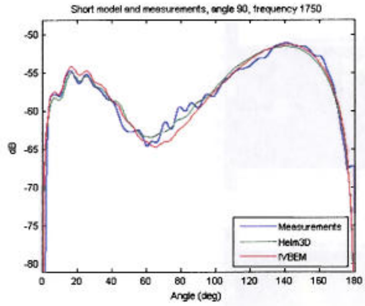
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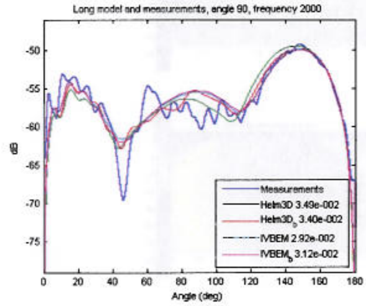
IVBEM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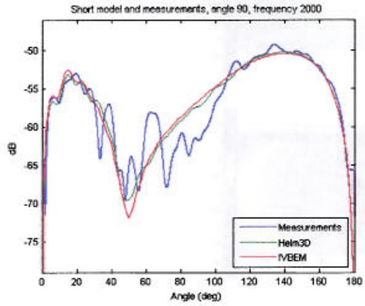
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Measurements
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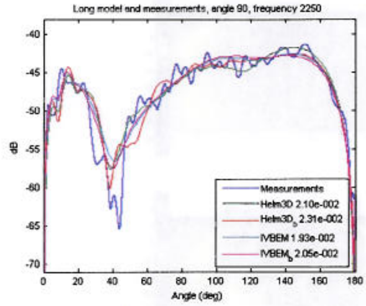
IVBEM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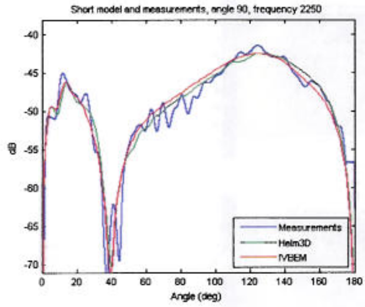
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Measurements
Helm3D
IVBEM

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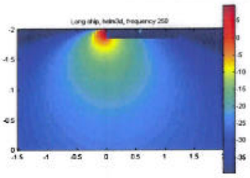

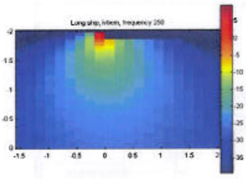

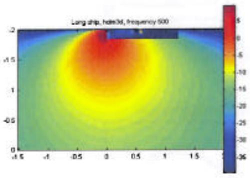

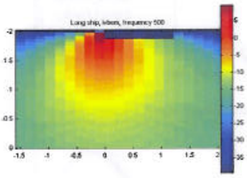

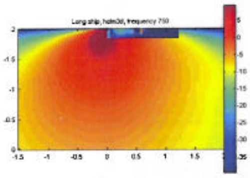

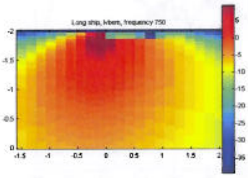

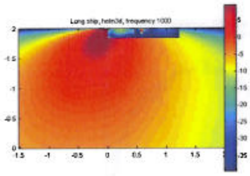

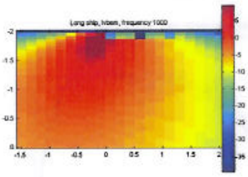

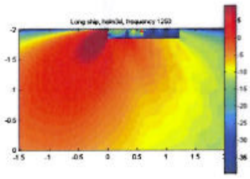

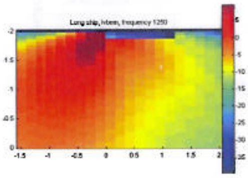

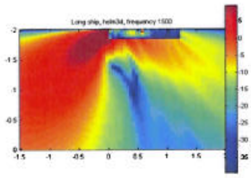

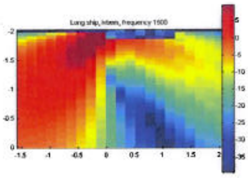

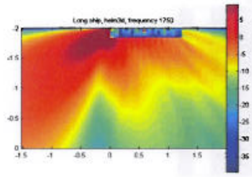
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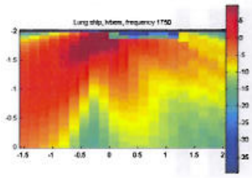
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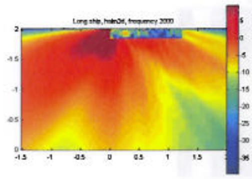
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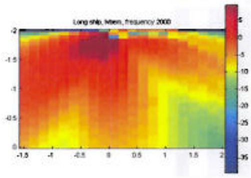
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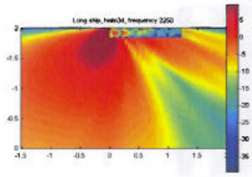
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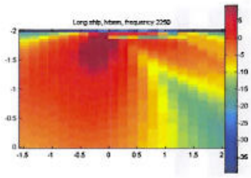
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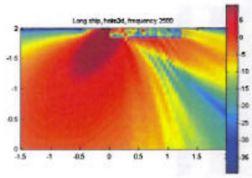
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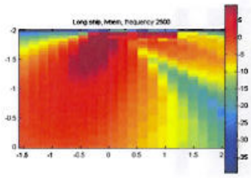
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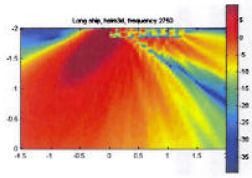
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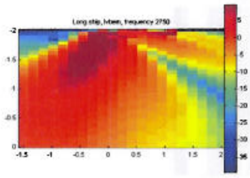
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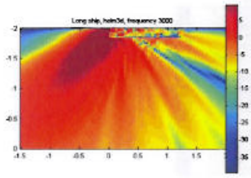
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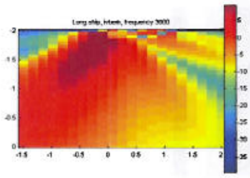
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0
-1.5
-1
-0.5
0
0.5
1
1.5
2
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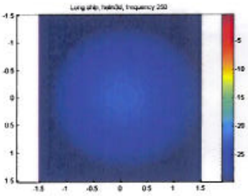
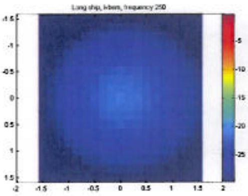
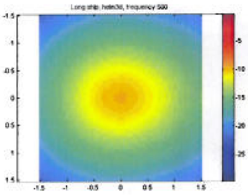
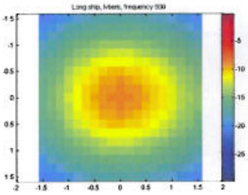
0
-5
-10
-15
-20
-25
-30
-35


Long ship, helm3d, frequency 250


Long ship, ivbem, frequency 250


Long ship, helm3d, frequency 500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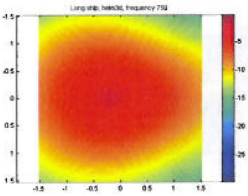
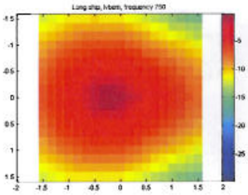
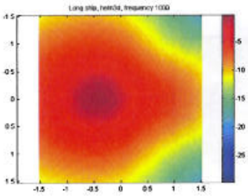
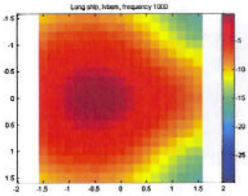
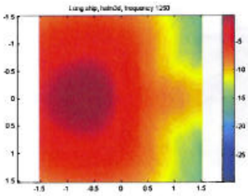
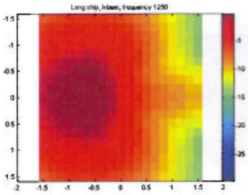

Long ship, helm3d, frequency 750

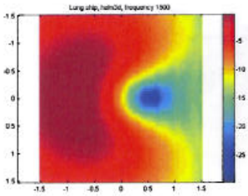

Long ship, ivbem, frequency 750

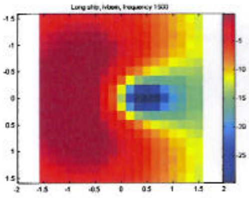

Long ship, helm3d, frequency 1000

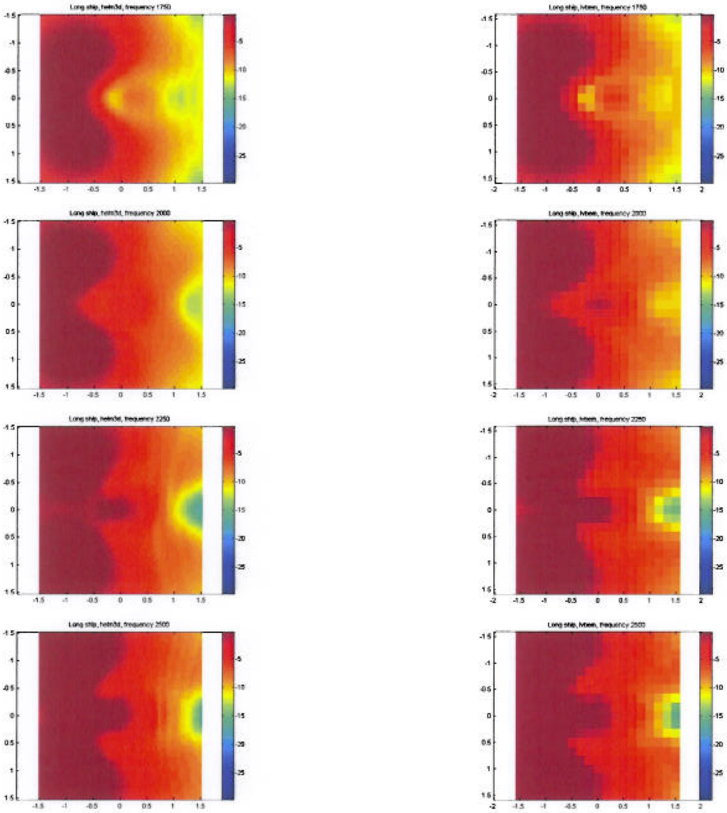

Long ship, ivbem, frequency 1000


Long ship, helm3d, frequency 1250


Long ship, ivbem, frequency 1250


Long ship, helm3d, frequency 1500


Long ship, ivbem, frequency 1500


Long ship, helm3d, frequency 1750
Long ship, lvbem, frequency 1750
Long ship, helm3d, frequency 2000
Long ship, lvbem, frequency 2000
Long ship, helm3d, frequency 2250
Long ship, lvbem, frequency 2250
Long ship, helm3d, frequency 2500
Long ship, lvbem, frequency 2500