Minimalistic bem code for plane wave scattering from underwater targets

MM 8.8.2025

mm-bem contains collection of several source codes for calculating scattering pattern obtained when plane wave scatters from soft targets. It uses boundary element method with piecewise constant discontinuous finite elements in 3D (P0).

Calling convension depends on the code language but usually it uses four parameters:

1. mesh file name in msh ascii 2.2 format (defaults to sphere-1.905-600.msh representing 1.905cm radius sphere defined with 600 points and 1196 triangles)
2. direction angle (defaults to θ = 0 what means that it travels along x axis)
3. frequency (defaults to f = 38kHz)
4. sound speed (defaults c = 1480m/s)

The most often results are printed into standard output in the form of two-column data containing:

1. scattering angle in degrees
2. absolute value of scattering length.

This output data could be redirected to txt file or piped to plotting software. The polar scattering strength in logarithmic domain could be obtained by gnuplot polar.gp script. The target strength is the value calculated at 180° distance from wave direction angle.

The source codes are in C, Python, Matlab, Julia and FreeFem. The theoretical calculations for a soft sphere are in Gnuplot. The example results are for 38kHz. The usege of source codes requires installating its evironments or comilers. Only FreeFem version uses Hmatrix approach that allows for faster calculations for large meshes.

The package contains also the demonstration page that do not need any addition installation. The page allows generating sphere, spheroid or ellipsoid meshes and calculating scattering pattern for them. Moreover, it can present the results in polar form of calculated data along with other data file that could be added for comparison. This version can work rather with only medium size meshes!

Shell script

The run.sh script shows software versions used and calling examples generating results for 38kHz (default frequency) on MacBookPro M1 2021 Sequoia 15.5.

```
bash-3.2$ ./run.sh
#!/bin/bash -v

gcc --version
Apple clang version 17.0.0 (clang-1700.0.13.5)
Target: arm64-apple-darwin24.5.0
Thread model: posix
InstalledDir: /Library/Developer/CommandLineTools/usr/bin
julia --version
julia version 1.10.7
python3 --version
Python 3.13.3
freefem++-mpi
freefem++-mpi - version 4.15 (Fri May  2 13:38:38 CEST 2025 - git v
License: LGPL 3+ (https://www.gnu.org/licenses/lgpl-3.0.en.html)
...

gnuplot --version
gnuplot 6.0 patchlevel 2

gcc src/soft.c -O3 -ffast-math -o bin/soft
time ./bin/soft msh/sphere-1.905-600.msh > out/sphere-1.905-0-38-14

real    0m0.658s
user    0m0.498s
sys    0m0.005s
time julia src/soft.jl msh/sphere-1.905-600.msh > out/sphere-1.905-

real    0m1.881s
user    0m2.933s
sys    0m1.405s
time python3 src/soft.py msh/sphere-1.905-600.msh > out/sphere-1.90

real    0m4.663s
user    0m4.461s
sys     0m0.078s
time freefem++-mpi -v 0 -f src/soft.edp > out/sphere-1.905-0-38-148

real    0m6.452s
user    0m6.379s
sys    0m0.044s
time python3 src/soft-bempp.py msh/sphere-1.905-600.msh > out/spher
```

```

real    0m10.900s
user    0m11.660s
sys     0m0.633s
time gnuplot -c src/soft.gp > out/sphere-1.905-0-38-1480-gp.txt

real    0m0.061s
user    0m0.044s
sys    0m0.007s

cd out
gnuplot -p -c ../bin/polar.gp sphere-1.905-0-38-1480*.txt
qt.qpa.fonts: Populating font family aliases took 56 ms. Replace use
mv polar.svg ../figs/sphere-1.905-0-38-1480.svg
mv polar.pdf ../figs/sphere-1.905-0-38-1480.pdf

gnuplot -p -c ../bin/polar.gp YFT*.txt
qt.qpa.fonts: Populating font family aliases took 58 ms. Replace use
mv polar.svg ../figs/YFT-0-38-1480.svg
mv polar.pdf ../figs/YFT-0-38-1480.pdf
cd ..
bash-3.2$
```

Note

For larger meshes Hmatrix based calculations is the requirement. Note the time of execution for YFT_swimbladder_origin.msh having 7502 mesh points for plain C version with gauessian elimination and FreeFem version and Bempp version with Hmatrix representation:

```
bash-3.2$ time ./bin/soft msh/YFT_swimbladder_origin.msh > out/YFT_s

real    15m17.280s
user    15m3.151s
sys.    0m9.557s
bash-3.2$ time freefem++-mpi -v 0 -ng -f src/soft.edp -fm msh/YFT_sw

real    1m51.404s
user    1m50.658s
sys     0m0.735s
bash-3.2$ time python3 src/soft-bempp.py msh/YFT_swimbladder_origin 
qt.qpa.fonts: Populating font family aliases took 57 ms. Replace use

real    0m45.726s
user    3m7.397s
sys    0m43.740s
bash-3.2$
```

Browser mm-bem viewer

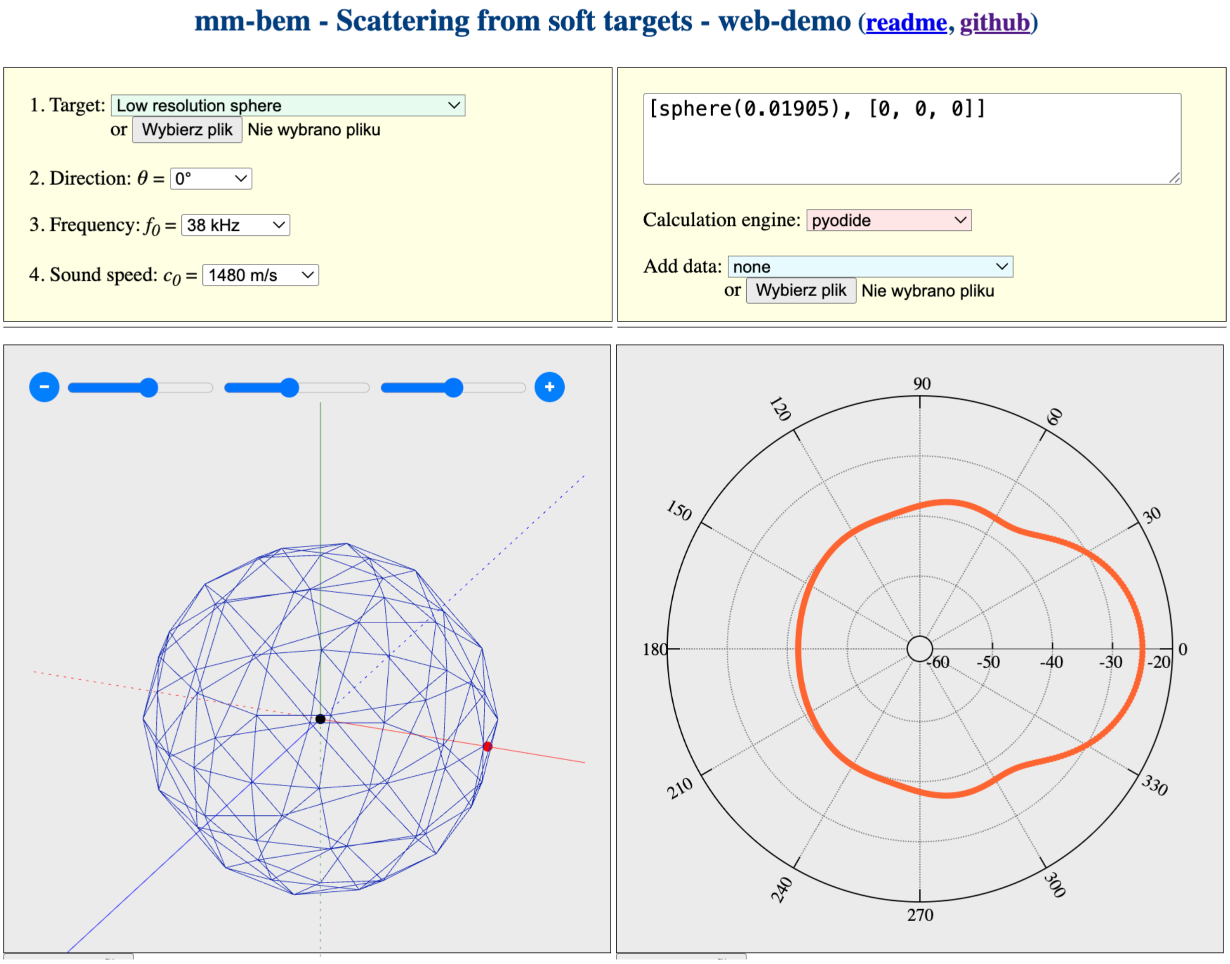


Fig. 8. The screendump from mm-bem web-demo for low resolution mesh of 1.905 cm radius sphere along with theoretical curve for soft sphere in salt water $c_0 = 1480$ m/s at 38kHz.

Examples

1. Soft scattering

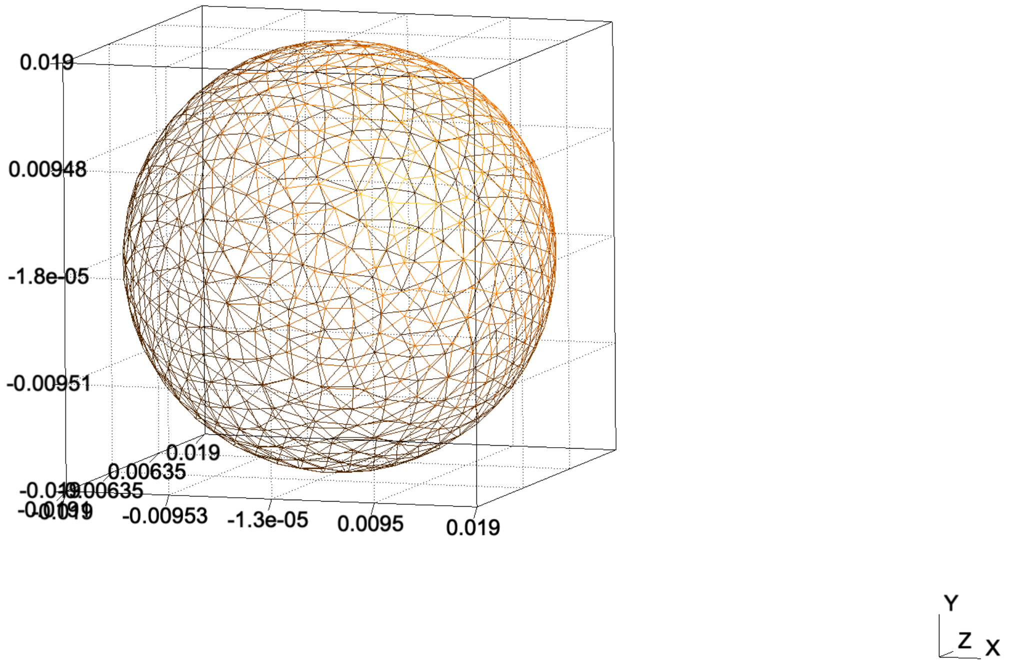


Fig. 1. The sphere mesh with radius of $a = 1.905$ cm having 600 nodes and 1196 triangular elements used for verification.

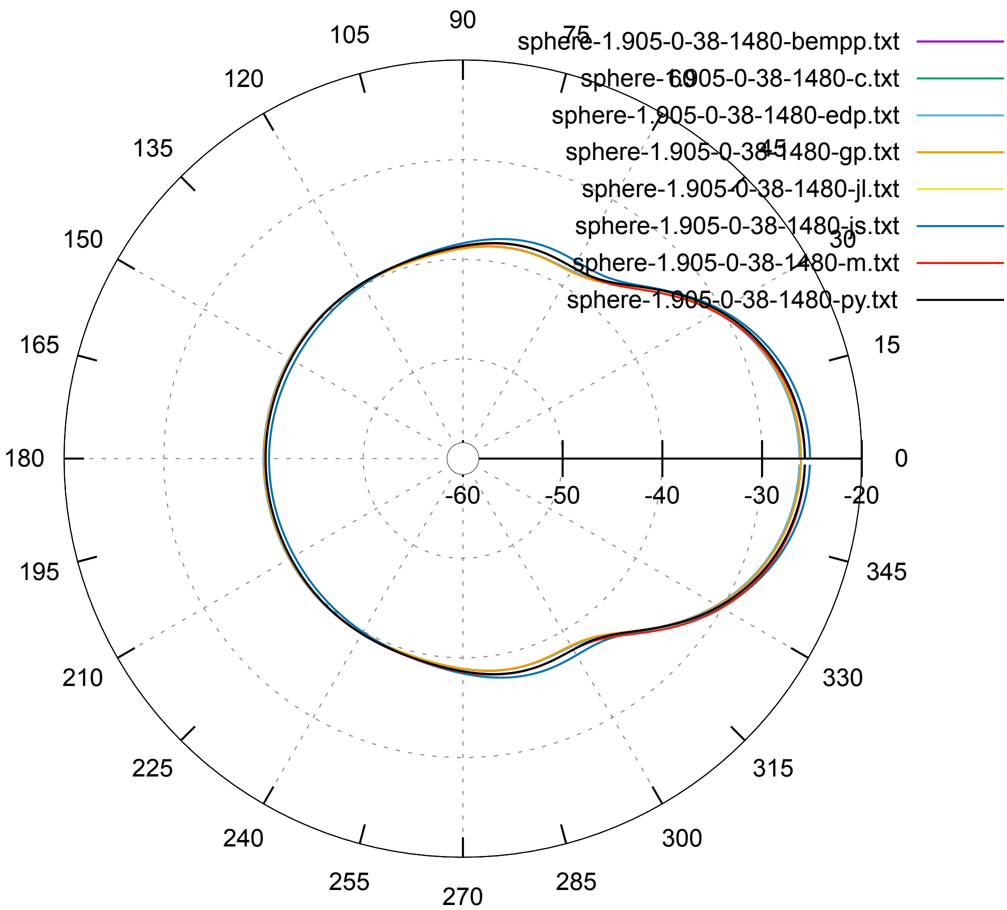


Fig. 2. The results obtained with codes written in several languages for soft sphere with radius of $a = 1.905$ cm in salt water $c_0 = 1480$ m/s at 38kHz.

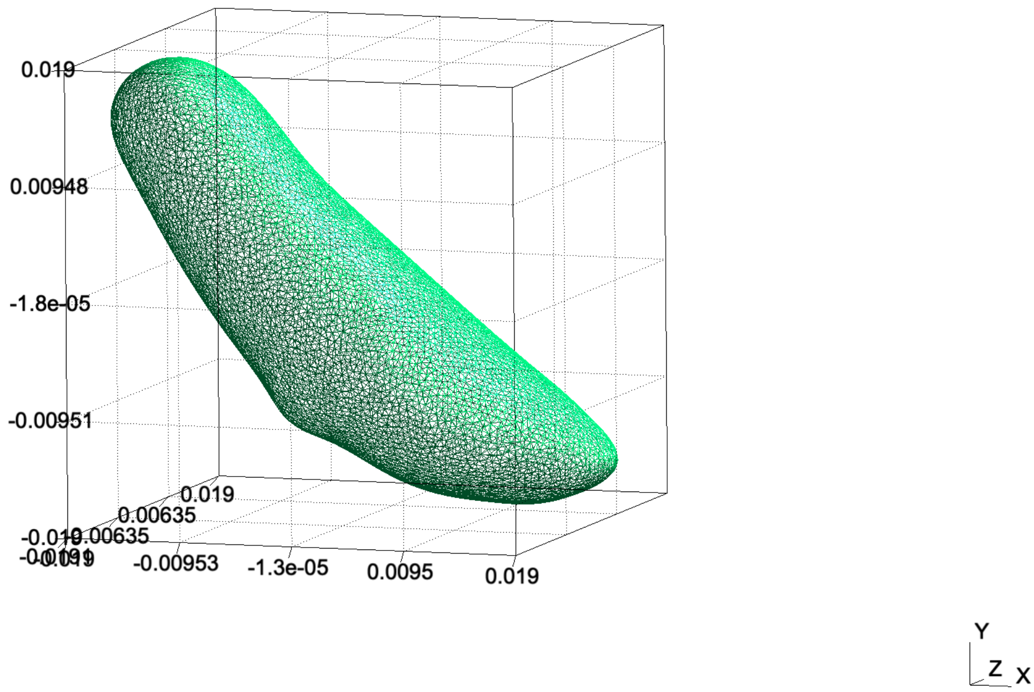
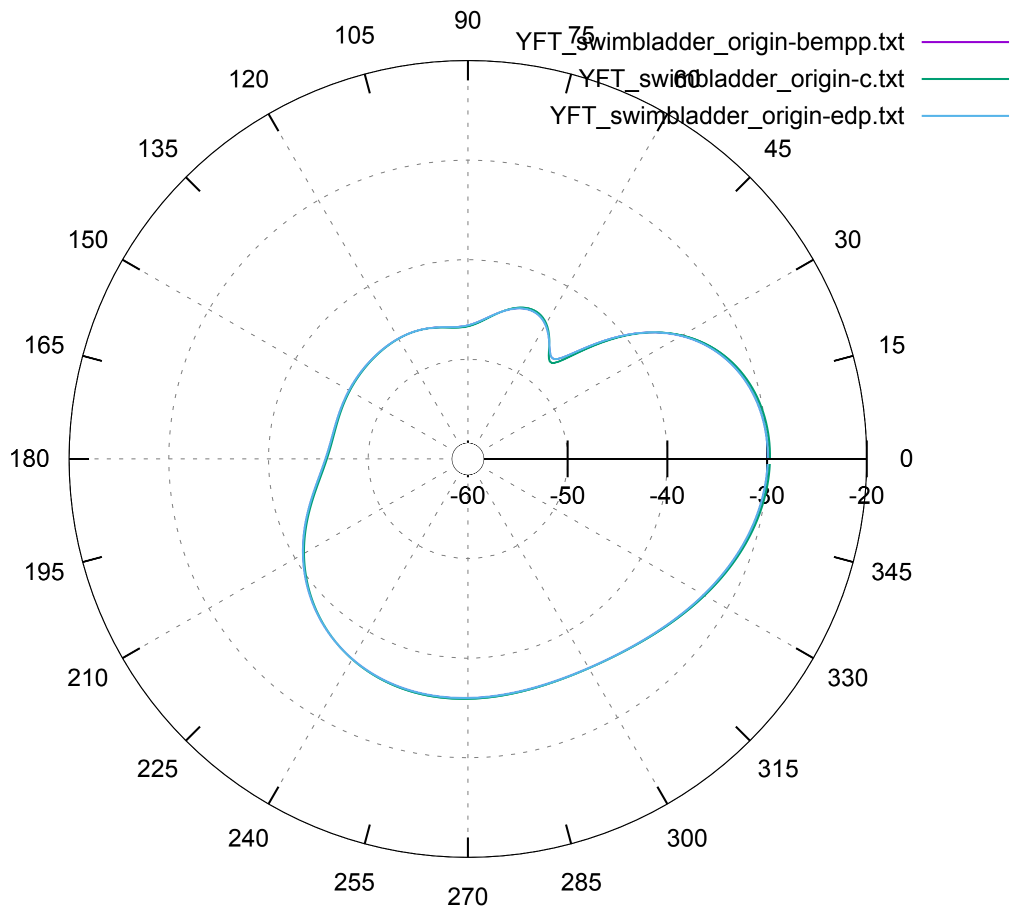


Fig. 3. The Yellow Fin Tuna swimbladder having 7502 nodes and 15000 triangular elements.



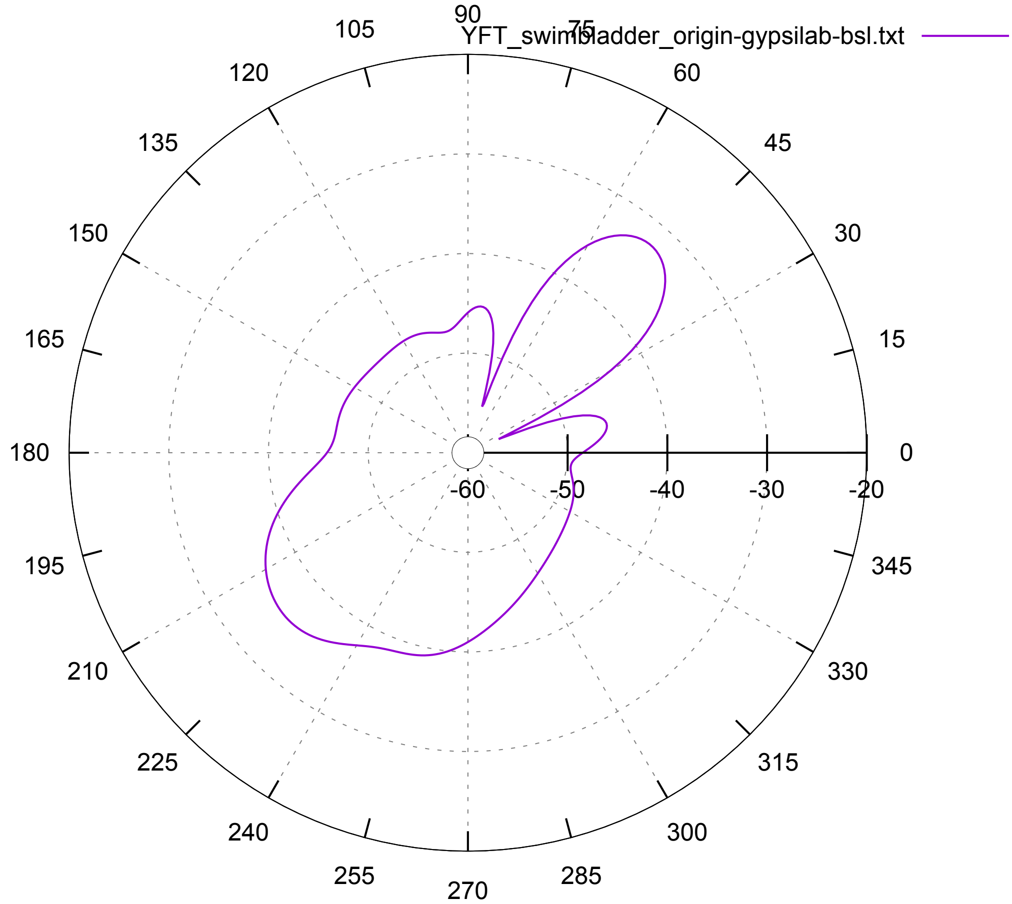


Fig. 4. The scattering pattern for plane wave comming from x-axis and full target strength pattern for (vacuum filled) YFT swimbladder in salt water $c_0 = 1480$ m/s at 38kHz.

2. Fluid scattering

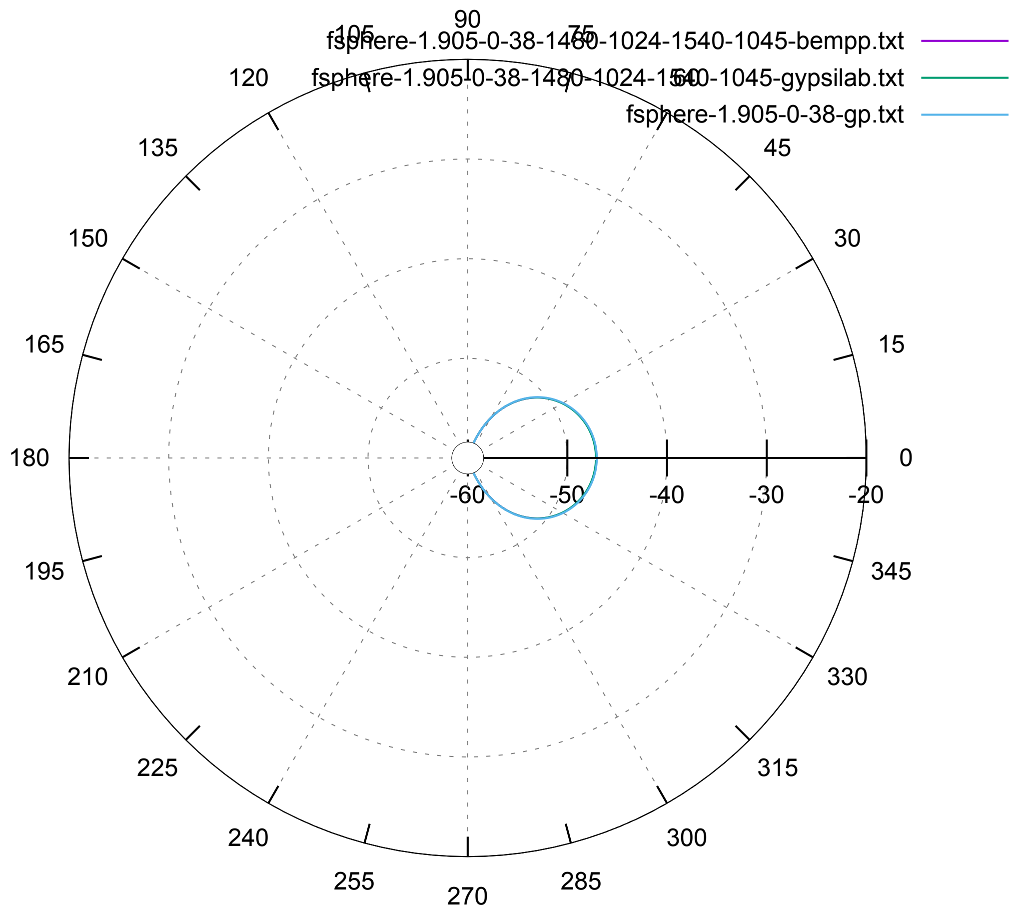


Fig. 5. The scattering from fluid sphere from Fig.1 ($c_1 = 1540$ m/s, $\rho_1 = 1045$ kg/m^3) with radius of $a = 1.905$ cm in salt water ($c_0 = 1480$ m/s, $\rho_0 = 1024$ kg/m^3) at 38kHz. The results from bem calculations along with analytical solution.

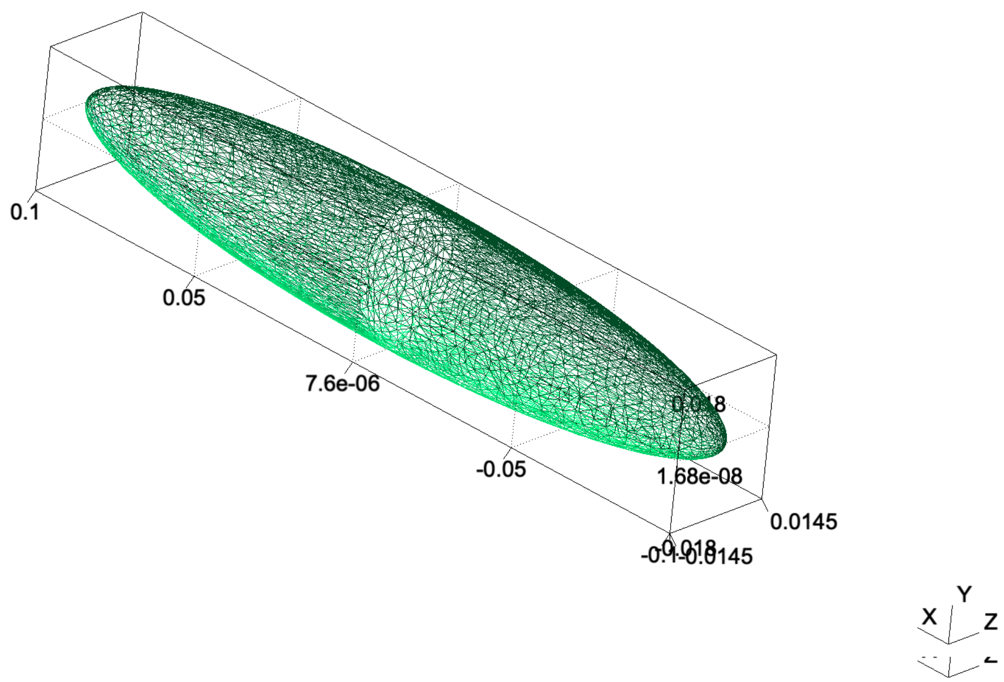
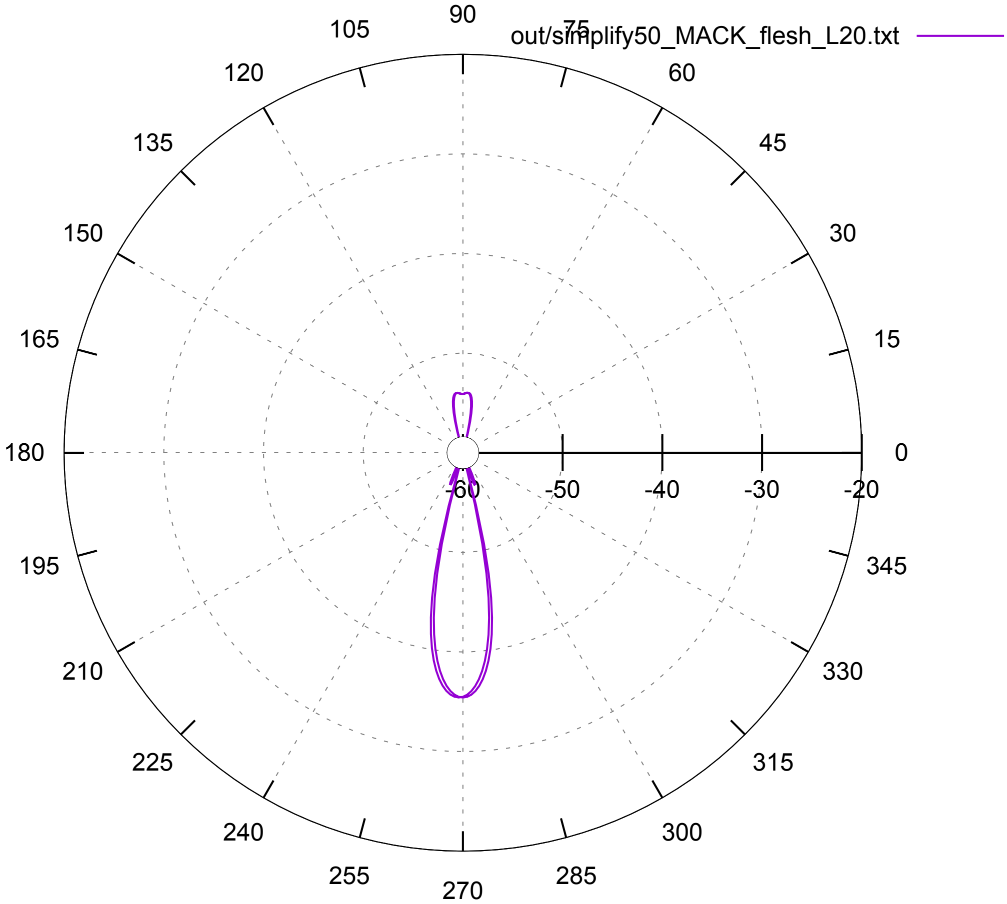


Fig. 6. The model of 20cm-length mackerel body.



out/simplify50_MACK_flesh_L20.txt
90
75
60
45
30
15
0
345
330
315
300
285
270
255
240
225
210
195
180
165
150
135
120
105
-60
-50
-40
-30
-20

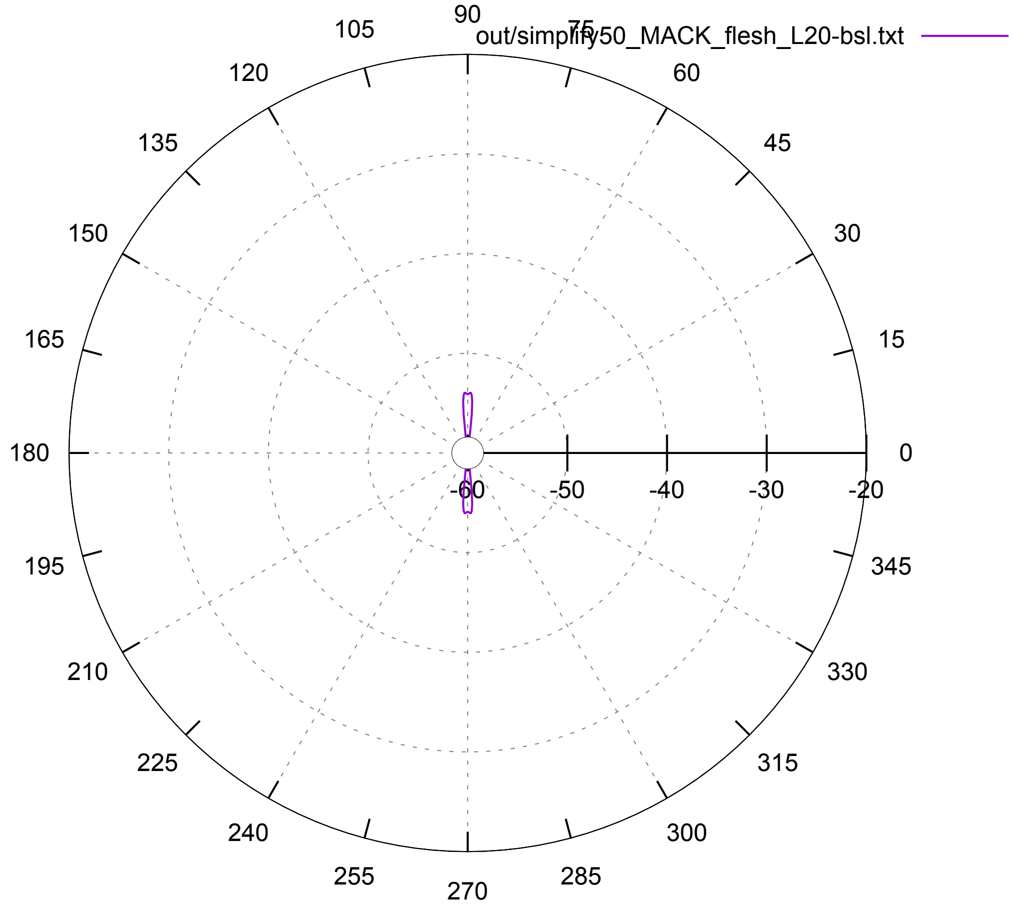


Fig. 7. The scattering pattern for dorsal insonification (from top of y-axis, TS value is at 90°) and xy-plane TS pattern at 38kHz assuming salt water medium ($c_0 = 1480$ m/s, $\rho_0 = 1024$ kg/m^3).

3. Shell scattering

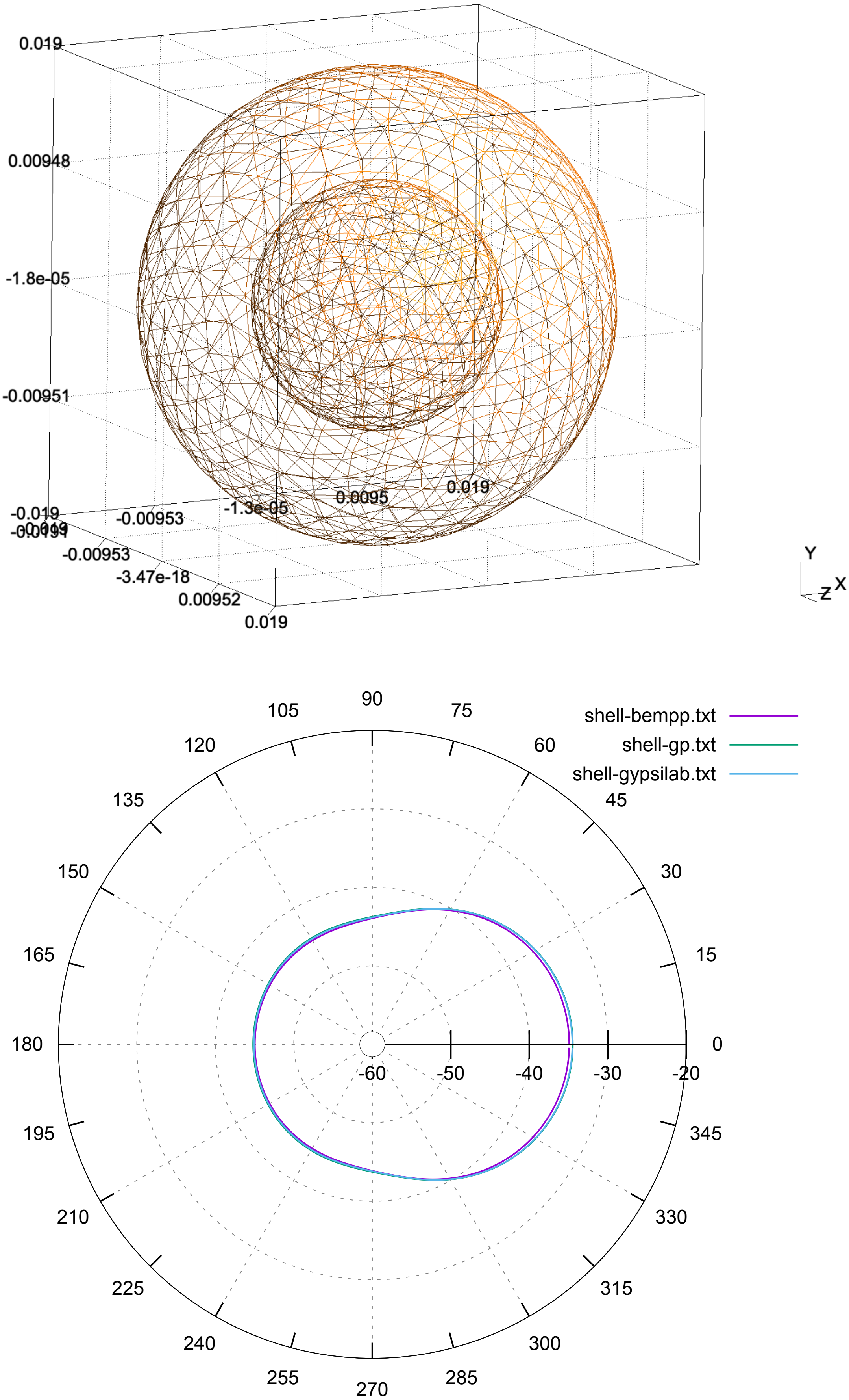
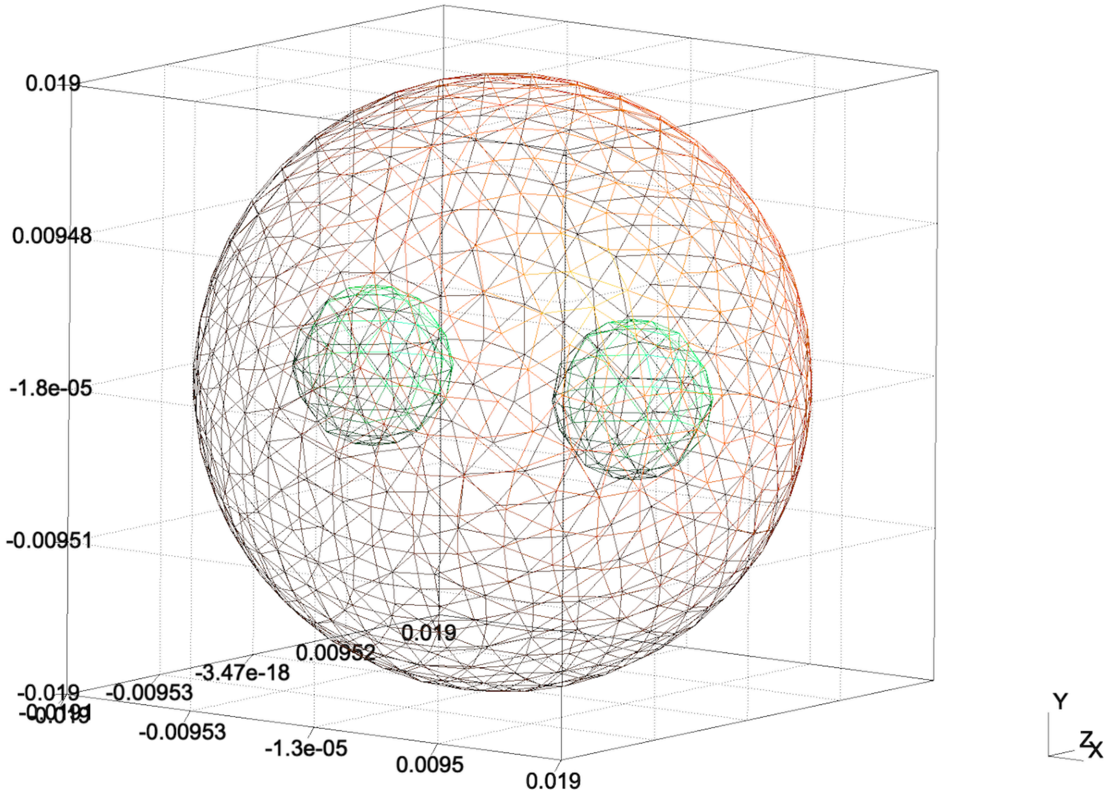


Fig. 8. The spherical shell mesh with $a_1 = 1.905$ cm (600 nodes) and $a_2 = 1.0$ cm (300 nodes) and its scattering pattern (bem and theory) at 38kHz assuming $c_0 = 1480$ m/s, $\rho_0 = 1024$ kg/m^3, $c_1 = 1540$ m/s, $\rho_1 = 1045$ kg/m^3, $c_2 = 340$ m/s, $\rho_2 = 1.29$ kg/m^3.

4. Scattering from two contrasting objects inside another one



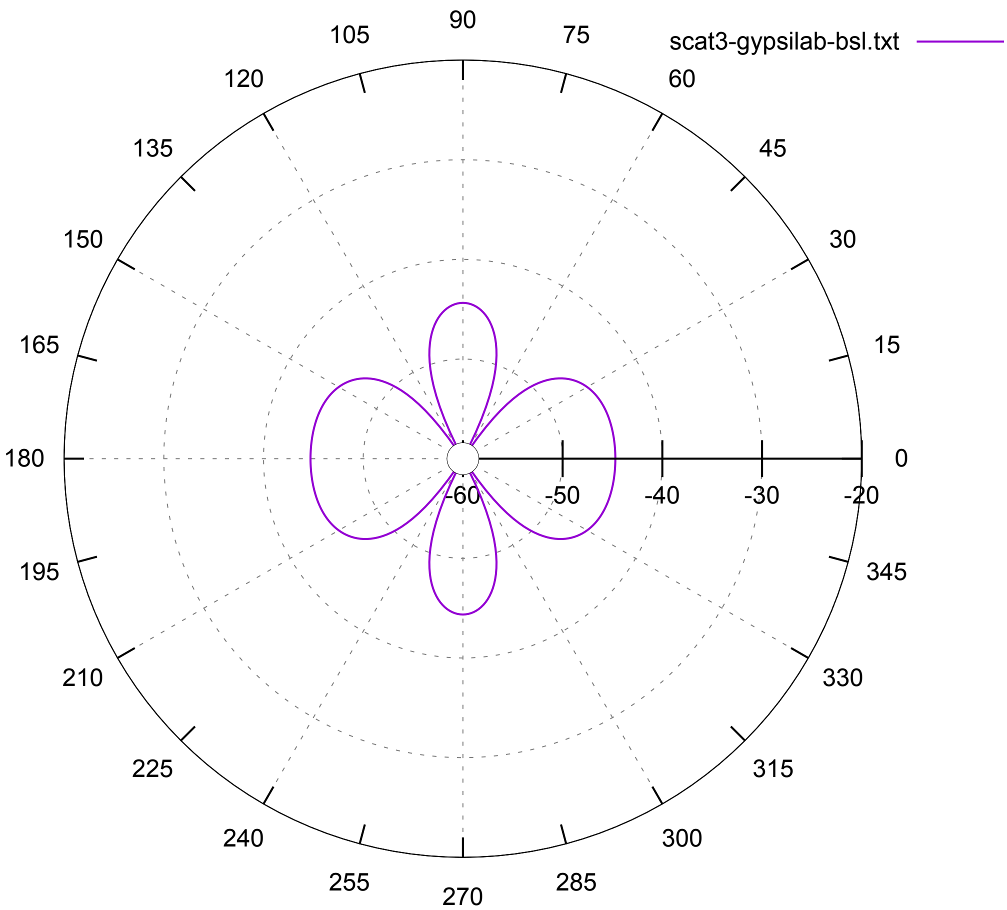


Fig. 9. The mesh of the sphere with two small spheres having different contrast: $a_1 = 1.905$

cm (600 nodes) and $a_2 = a_3 = 0.5$ cm (200 nodes) and its target strength pattern (bem results) at 38kHz assuming $c_0 = 1480$ m/s, $\rho_0 = 1024$ kg/m^3, $c_1 = 1540$ m/s, $\rho_1 = 1045$ kg/m^3, $c_2 = c_3 = 340$ m/s, $\rho_2 = \rho_3 = 1.29$ kg/m^3.