NEMOH
User Manual

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Preamble

0.1 Introduction

This document is the Manual of NEMOH Software that serves as a guide for using and running the software.

NEMOH solves linear diffraction and radiation problems of wave-structure interaction by means of 3-D boundary element method in frequency domain. An extended module is available for computing difference- and sum- frequencies Quadratic Transfer Functions (QTFs) for fixed or floating structures.

Section 2 describes briefly the mathematical background and the capabilities of the software ; it is advised to read this Section before continuing to the rest of the manual.

Section 3 describes installation, running the codes and description input-output files.

Section 4 describes briefly test-cases that will show capabilities of the code and its use, and can be used as a first set-up for a desired computation.

The software has been written by G. Delhommeau, P. Guevel, J.C. Daubisse, J. Singh, A. Babarit, A. Combourieu, F. Robaux, R. Kurnia

0.2 Description of NEMOH

0.2.1 Introduction NEMOH

This section provides background information of NEMOH about the basic scientific ideas.

NEMOH is an open-source potential flow boundary element solver for computing first-order hydrodynamic coefficients in frequency domain. NEMOH has an extended module to post-process the first-order hydrodynamic results and compute complete Quadratic Transfer Functions (QTFs).

Underlying Modelling/Numerical Methods

NEMOH1, first order solver, is based on the following principles

— Potential flow problem for inviscid, incompressible fluid in irrotational motion and satisfying free-surface condition, impermeable bottom condition, diffraction and radiation conditions on body hull and radiation wave condition in far-field.

— Following convention of the harmonic fluid potential is used

$$\Phi(\boldsymbol{x},t) = Re\left\{\Phi^{(1)}(\boldsymbol{x})e^{-i\omega t}\right\}. \tag{1}$$

The total potential, Φ, is sum of the incident potential, the diffraction potential and the radiation potential. The incident potential is defined as, with k and ω related with the dispersion relation, $\vec{k} = k(\cos\beta, \sin\beta)$, β is wave direction, $\vec{x} = (x, y)$, water depth D, g is the gravity acceleration and a is an unit wave amplitude,

$$\Phi_I^{(1)}(\boldsymbol{x}) = -i\frac{ag}{\omega}\frac{\cosh(k(D+z))}{\cosh(kD)}e^{i\vec{k}\cdot\vec{x}}. \tag{2}$$

The radiation potential is defined as $\Phi_R(\boldsymbol{x},t) = Re\left\{\dot{\boldsymbol{\xi}}^{(1)}(t)\cdot\boldsymbol{\psi}(x)\right\}$ where $\boldsymbol{\xi} = (\boldsymbol{X},\boldsymbol{\theta})$ is the vector of body position, $\dot{\boldsymbol{\xi}}$ is the time derivative of $\boldsymbol{\xi}$, $\boldsymbol{X}$ and orientation $\boldsymbol{\theta}$, with respect to CoG and $\boldsymbol{\psi}(\boldsymbol{x})$ is the normalized vector radiation potential.

— The three-dimensional linear potential flow problem around arbitrary body condition is reformulated in the Boundary Integral Equation (BIE) and transformed into the two-dimensional problem of source distribution, σ, on body surface, S_B, using Green's second identity and the appropriate Green function, $G(\boldsymbol{x},\boldsymbol{x}')$.

— The Green-function is based on Delhommeau's formulation and available for finite and infinite water-depth [4].

— The source distribution depends on the considered boundary condition problem. For each frequency and wave-direction, the diffraction source distribution, $\sigma_D(\boldsymbol{x})$, depends the position of the panels while the radiation source distribution, $\sigma_{R_j}(\boldsymbol{x})$, depends on the position of the panels and the considered degree of freedom (DoF) $-j$.

— Then the BIE for $\boldsymbol{x}\in S_B$, is expressed as, with flow points $\boldsymbol{x}$ and source point $\boldsymbol{x}'$,

$$\frac{1}{2}\sigma_{D,R_j}(\boldsymbol{x}) - \frac{1}{4\pi}\int_{S_B}\partial_n G(\boldsymbol{x},\boldsymbol{x}')\sigma_{D,R_j}(\boldsymbol{x}')dS' = \mathcal{N}_{D,R_j}(\boldsymbol{x}). \tag{3}$$

where $\mathcal{N}(\boldsymbol{x})$ is the body normal condition. the diffraction normal condition is defined as $\mathcal{N}_D(\boldsymbol{x}) = -\partial_n\Phi_I^{(1)}(\boldsymbol{x})$, the normalized radiation condition, $\mathcal{N}_R(\boldsymbol{x}) =$

$\partial_n \Phi_{R_j}(\boldsymbol{x})$, with $\Phi_{R_j}(\boldsymbol{x})$ is the vector component-j of the normalized radiation potential $\boldsymbol{\psi}(\boldsymbol{x})$, explicitly $\boldsymbol{\psi} = (\Phi_{R_1}, \Phi_{R_2}, \cdots, \Phi_{R_{Ndof}})$.
- The BIE, Eq. 3, is discretised using the constant panel method, with quadrilateral mesh, leads to linear system with the influence coefficients Matrix. The mesh is user-specified with the normal-direction towards fluid.
- Gauss-quadrature integration is applied, with an user-input number of Gauss-quadrature points, in the integration over panel for constructing the influence coefficients.
- The linear system is then solved using a user-choice solver which the available solvers are Gauss elimination, LU-decomposition (default) and GMRES-iterative solver.
- The GMRES solver code [10] from CERFACS is embedded in NEMOH solver module. For using the GMRES solver, user has to obtain a license in `https://www.cerfacs.fr/algor/Softs/GMRES/license.html`.
- The source distributions on body panels are then obtained after solving corresponding problems of the linear system.
- The diffraction potential, $\Phi_D^{(1)}$, the normalize radiation potential vector component-j, $\Phi_{R_j}^{(1)}$ and the corresponding velocities are then computed as follows, for the flow points in the fluid domain $\boldsymbol{x} \in S_B \cup V_{\Omega_F}$,

$$\Phi_{D,R_j}^{(1)}(\boldsymbol{x}) = -\frac{1}{4\pi}\int_{S_B} G(\boldsymbol{x},\boldsymbol{x}')\sigma_{D,R_j}(\boldsymbol{x}')dS' \tag{4}$$

$$\partial_{\boldsymbol{x}}\Phi_{D,R_j}^{(1)}(\boldsymbol{x}) = \frac{1}{2}\sigma_{D,R_j}(\boldsymbol{x})\boldsymbol{n}\delta_{\boldsymbol{x}\boldsymbol{x}'} - \frac{1}{4\pi}\int_{S_B}\partial_{\boldsymbol{x}} G(\boldsymbol{x},\boldsymbol{x}')\sigma_{D,R_j}(\boldsymbol{x}')dS' \tag{5}$$

  where the Kronocker delta $\delta_{\boldsymbol{x}\boldsymbol{x}'} = 1$ for $\boldsymbol{x} = \boldsymbol{x}'$, $\delta_{\boldsymbol{x}\boldsymbol{x}'} = 0$ otherwise.
- The hydrodynamic coefficients are then computed as follows, the excitation force is defined as, with the generalized normal vector $\boldsymbol{\nu} = (\boldsymbol{n}, \boldsymbol{r}\times\boldsymbol{n})^T$,

$$\boldsymbol{F}_{exc}^{(1)} = \rho\iint_{S_B} -i\omega\left[\Phi_I^{(1)} + \Phi_D^{(1)}\right]\boldsymbol{\nu}dS. \tag{6}$$

  The added mass matrix and damping coefficient matrix components are computed as

$$M_{ij}^a = -\rho\iint_{S_B}\nu_i Re\left\{\psi_{R_j}\right\}dS \tag{7}$$

$$B_{ij} = -\rho\omega\iint_{S_B}\nu_i Im\left\{\psi_{R_j}\right\}dS. \tag{8}$$

- In post-processing, the radiation damping impulse response matrix function ($\boldsymbol{IRF}(t)$), infinite frequency added mass matrix ($[\boldsymbol{M}^a](\infty)$), the excitation force impulse response vector function ($\boldsymbol{IRF}_{ex}(t)$) that are computed as,

$$\boldsymbol{IRF}(t) \approx \frac{2}{\pi}\int_0^{\omega_{max}}[\boldsymbol{B}](\omega)\cos(\omega t)d\omega,$$

$$[\boldsymbol{M}^a](\infty) \approx \frac{1}{N_\omega}\sum_{i=1}^{N_\omega}[\boldsymbol{M}^a](\omega_i) + \int_0^{t_{max}}\boldsymbol{IRF}(t)\sin(\omega_i t)dt$$

$$\boldsymbol{IRF}_{exc}(t) \approx \frac{1}{2\pi}\int_{-\omega_{max}}^{\omega_{max}}\boldsymbol{F}_{exc}(\omega)\exp(-i\omega t)d\omega.$$

where $\boldsymbol{F}_{exc}(-\omega) = \boldsymbol{F}^*_{exc}(\omega)$. Note that ω_{max} is a user-specified input, for better accuracy of $\boldsymbol{IRF}(t)$ make sure that $[\boldsymbol{B}](\omega_{max})$ has reached an asymptotic value.
- Response Amplitude Operators (RAO) are obtained by solving following equation of motion

$$\left[-[\boldsymbol{M} + \boldsymbol{M}^a(\omega)]\omega^2 - i\omega[\boldsymbol{B}(\omega) + \boldsymbol{B}_{add}] + [\boldsymbol{K}_h + \boldsymbol{K}_M]\right] \boldsymbol{\xi}(\omega) = \boldsymbol{F}_{exc}(\omega)$$

where $[\boldsymbol{B}_{add}]$ and $[\boldsymbol{K}_M]$ are user-specified additional damping and stiffness matrices. LU-decomposition is used for obtaining the inverse matrix.
- For free-surface piercing bodies problem, the irregular frequencies removal method is applied by user providing lid panels at $z = 0$. Then the extended boundary integral equation will be solved.
- The software can solve multi-bodies problem, multi-directional waves.

NEMOH2, QTF module, is based on the following principles
- The QTF module can be run only after the first order-hydrodynamic coefficients computed.
- The second order loads are composed by the quadratic part and the potential part, the detail formulation is given in [8, 9].
- The quadratic part is based on the near-field method [3].
- The potential part is based on the indirect method [3, 6].
- In the potential part, the free-surface integral is an option to be computed. Computation of the free-surface integrals is necessary for the sum-frequency QTFs.
- For the free-surface integral, a free-surface mesh has to be specified.
- The computation can be done for bi-directional or uni-directional wave for the specified multiple wave direction.
- It has not tested yet for the multi-bodies problem.

NEMOH related publications to be referred are [1] for the first order NEMOH and [8, 9, 7] for the QTF module.

0.2.2 Units

NEMOH expects all quantities to be expressed in S.I. units : m, kg, s, deg (meter, kilogram, seconds, degree, respectively). But some the phase output may be expressed in rad, it will be indicated in header of the file. The degree symbol may be also denoted as $^\circ$.

The force unit is $[N]$, moment unit is $[Nm]$, added Mass $[kg]$, damping coefficient $[kg/s]$. As the force output is normalized with the unit wave amplitude a $[m]$, then the normalized force unit is $[N/m]$ and the normalized moment is $[N]$.

Response amplitude operator for translation motion has unit $[m/m]$ and for rotation is $[deg/m]$.

The force quadratic transfer function (QTF) has unit $[N/m^2]$ and for the moment QTF is $[N/m]$. The QTF output is then also normalized by ρg where the fluid density ρ, $[kg/m^3]$, and the gravitation constant g, $[m/s]$.

0.2.3 Software feature and capabilities

Fig. 1 shows global overview of the software. There are three main programs : a mesh generator, NEMOH1 and NEMOH2. The program features and capabilities are described

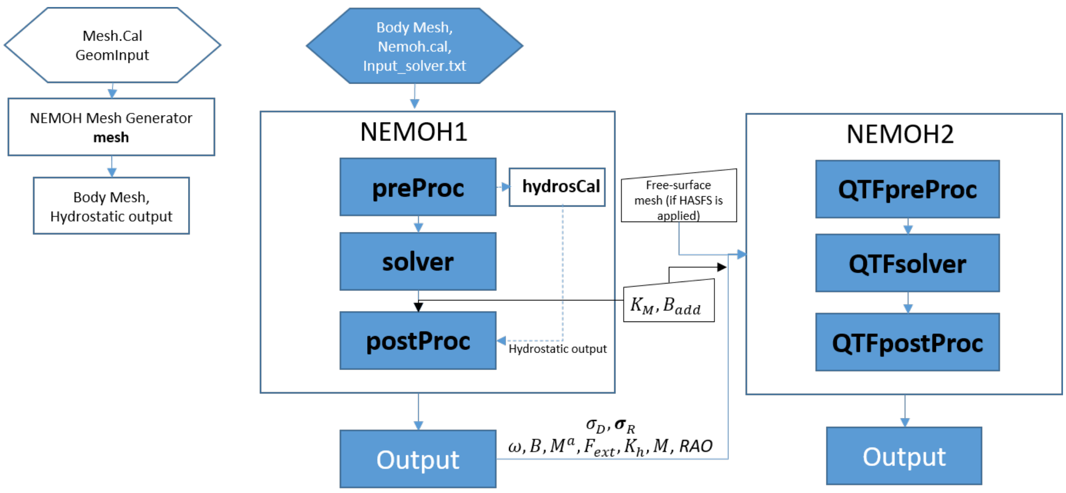

FIGURE 1 – Global flowchart of NEMOH software

as follows.

Mesh Generator

NEMOH mesh generator, the executable file '**mesh**', is for generating NEMOH mesh file for given a geometry input file and Mesh.Cal file. This '**mesh**' is a not meshing code but allows to to refine a mesh and to calculate properties such as displacement, buoyancy center, hydrostatic stiffness. It also makes estimate of masses and inertia matrix. The concept with this software is to write by hand a coarse description of the body under consideration in a GeomInput file and to have '**mesh**' make the refined mesh for NEMOH calculations.

External mesh generators, i.e. the open-source software gmsh [5], may be used with the generated mesh file must be adapted with the NEMOH format. In this case, the hydrostatic properties can still be computed by **hydrosCal** after **preProc**.

NEMOH1 : 1st order solver

NEMOH1 solves the first-order potential flow problem. There are four modules : **preProc**, **hydrosCal**, **solver** and **postProc**, described as follows.

- **preProc** : processing the input mesh file and generates the body condition for each calculation case (diffraction and radiation). The outputs are used as input for **solver**.
- **hydrosCal** : computes hydrostatic parameters, i.e. stiffness matrix, inertia matrix. The output file will be used in the postProc for computing RAO. If the input mesh is generated by the NEMOH mesh generator, **mesh**, the hydrostatic parameter is also computed then it is not necessary to execute this program.
- **solver** : solving the boundary value problems for each problem, radiation and diffraction, defined in the file Normalvelocities.dat, provided by the **preProc**.
  - The influence coefficient matrix is constructed with the infinite/finite depth green function.
  - If a finite depth is specified, then the finite depth green function is applied only for $\frac{\omega^2}{g}D < 20$, otherwise infinite depth case applied.

  - The integration of the Green-function in a panel for the influence coefficients are obtained by the Gauss-quadrature integration. The number of Gauss quadrature point is a user-input.
  - The minimum distance, ϵ, between flow and source points for the influence coefficient computation is user-specified.
  - The source distributions are then obtained by solving the linear system. There are three options for the solver : Gauss elimination, LU-decomposition and GMRES. In the case the GMRES solver [10] used and the specified tolerance not achieved after the maximum iteration, the problem is automatically solved by LU-decomposition. License for using GMRES has to be obtained in `https://www.cerfacs.fr/algor/Softs/GMRES/license.html`.
- **postProc** : postprocessing the solver output files. As results are the excitation forces, added mass and damping coefficients. As options, the program computes
  - the radiation damping impulse response function, the infinite frequency added mass and the excitation force impulse response function,
  - the Kochin coefficient,
  - the free-surface elevation,
  - the motion response amplitude operator (RAO), additional stiffness matrix $[\boldsymbol{K}_m]$ and additional damping $[\boldsymbol{B}_{add}]$ can be user-specified in the Mechanics folder.

NEMOH2 : QTF module

NEMOH2 computes the second-order wave loads that expressed in Quadratic Transfer Function (QTF). It is suggested to verify the first-order results before running the QTF module. There are three modules in this program : **QTFpreProc**, **QTFsolver** and **QTFpostProc**, described as follows

- **QTFpreProc** : preparing the perturbed potential, the total potential, the normalized radiation potential and the corresponding velocities on the body panels, the water-line and the free-surface panels.
  - The computation on free-surface panels requires longer computation time, so for the first-time it is suggested to compute without the Free-surface integral, HASFS, the option available in Nemoh.cal.
  - The potential on waterline is rather sensitive with the ϵ value. For default, $\epsilon = 0.001$, it can be adjusted in input_solver.txt. The ϵ can be set different for NEMOH1 and NEMOH2. Further investigation about this is needed.
  - In case the lid-panels exist, the influence coefficient is affected and gives somewhat larger error for higher frequencies the free-surface potentials and velocities. This is also need to be investigated.
- **QTFsolver** : computing the quadratic part and the potential part of the second order loads. The free-surface integrals in the potential part QTF is an option to be computed.
- **QTFpostProc** : summing all the computed QTF parts and produces the total QTF. Option to sum only some parts of QTF is available in Nemoh.cal.

0.3 Getting-started

This section describes installation, running the codes and description input-output files.

0.3.1 Executable files

Executable/binary files are provided in folder '/bin' and can be used by user directly without need to do the compilation process in the next-subsection. Following are the executable files :

- NEMOH1 : **mesh**, **preProc**, **hydrosCal**, **solver**, **postProc**,
- NEMOH2 : **QTFpreProc**, **QTFsolver**, **QTFpostProc**.

0.3.2 Installation

This step is intended for a developer to do compilation after changing the source code. User may skip this step.

Two *Makefile* are provided with the source code for compiling NEMOH1 and NEMOH2 in Linux/Unix environment. The intel fortran compiler, ifort, or the GNU fortran compiler, gfortran, may be used.

An external library, LAPACK, need to be installed before the compilation. The detail of LAPACK can be found in `https://netlib.org/lapack/`.

Following are the commands for compiling NEMOH1 and NEMOH2 in the command window :

- make all % this produces all NEMOH1 executable files
- make -f makefile_QTF install % this produces all NEMOH2 executable files.

Other commands can be used, i.e 'make solver' for compiling only solver module,'make clean_all' for the cleaning modules and the binary files, etc, the detail can be seen in the makefile.

The compilation produces the executable/binary files in the folder '/bin'.

0.3.3 Running

The binary files of NEMOH1 and NEMOH2 have to be executed in the order as in subsection 0.3.1. If the binary file exists but there is no access to be executed, in the command window type chmod +x 'binfile' that will add the executable access to the 'binfile'.

Following steps are for executing the binary files in the command window.

- Suppose a project directory in, i.e '/NEMOH/projdir/', that contains all the input files, is in the same location as the binary directory, i.e 'NEMOH/bin/'.
- The program can be run depend on your current working directory in the command line (type 'pwd' for checking). For examples, the following commands are possible, with binfile is an executable file i.e. preProc, etc., as
  - if you are in the projdir : ./../bin/binfile
  - if you are in the bin : ./binfile ./../projdir

Before executing the binary files, the input files are needed. The input files are described in the next subsection.

For starting, the 'make' commands for running the provided test-cases are available, type in the command window :

— make run_1_cylinder
— make run_2_2Bodies
— make run_3_nonsymmetrical
— make run_4_postprocessing
— make run_5_quicktest
— make run_6_box_coarsemesh,

and following commands for running the QTF test-cases :

— make -f makefile_QTF run_7_QTF_Cylinder
— make -f makefile_QTF run_8_oc4_semisub
— make -f makefile_QTF run_9a_softwind
— make -f makefile_QTF run_9b_softwind_FS.

Clean commands, i.e make clean_1_cylinder, are also provided in the makefile to remove all the output files.

Description and the benchmark results of the verification case are described in next section.

0.3.4 Input/Output

Following are the list of the user's input files and the output files for each program :

- **mesh**
  - User's input files : projdir/mesh.cal, projdir/geomInput,
  - Output files : projdir/meshfile, projdir/mesh/[*.dat, *.tec],
- **preProc**
  - User's input files : projdir/Nemoh.cal, projdir/meshfile,
  - Output files : projdir/Normalvelocities.dat,
    projdir/results/[FKForce.dat, FKForce.tec, index.dat],
    projdir/mesh/[L10.dat, L12.dat],
- **hydrosCal**
  - User's input files : projdir/Nemoh.cal, projdir/mesh.cal,
  - Output files : projdir/mesh/[*.dat, *.tec], projdir/Mechanics/,
- **solver**
  - User's input files : projdir/Nemoh.cal, projdir/input_solver.txt
  - Output files : projdir/results/Forces.dat,
    projdir/results/sources (if QTF will be computed, indicated in Nemoh.cal)
- **postProc**
  - User's input files : projdir/Nemoh.cal, projdir/Mechanics/[Km.dat,Badd.dat]
  - Output files : projdir/results/[ExcitationForce.tec,DiffractionForce.tec,
    RadiationCoefficients.tec,$\cdots$], projdir/Motion/RAO.dat,
- **QTFpreProc**
  - User's input files : projdir/Nemoh.cal, projdir/FSmeshfile (If the free-surface integral, HASFS, is computed), projdir/Mechanics/[Km.dat,Badd.dat]
  - Output files : projdir/QTFPreprocOut/*.bin,
- **QTFsolver**
  - User's input files : projdir/Nemoh.cal
  - Output files : projdir/results/QTF/*.dat,
- **QTFpostproc**
  - User's input files : projdir/Nemoh.cal
  - Output files : projdir/results/QTF/[OUT_QTFM_N.dat,OUT_QTFP_N.dat]

As summary, following files are needed for the input, some depends on user-specified choice in *Nemoh.cal* :

— *Nemoh.cal* contains all NEMOH computation parameters
— a *meshfile*, input for **preProc**, or *geomInput* file, input for **mesh**
— *input_solver.txt* contains **solver** parameters
— *Km.dat* and *Badd.dat*, are the additional stiffness and damping matrices. These optional input are for **postProc/QTFpreProc**
— *FSmeshfile* contains the free-surface mesh if contrib=3.

NEMOH produces following main output files, some depends on user-specified choice in *Nemoh.cal*,

— hydrostatic files : inertia and stiffness matrices,
— hydrodynamics coefficients : Froude-Krylov force, excitation force, added-mass, damping coefficient,
— Kochin function, free-surface elevation,
— Response Amplitude Operator (RAO),
— Total difference- and sum-frequencies QTFs.

Detail description of the input/output files are discuss in next subsections.

User's input files

Nemoh.cal : contains all computation parameters with the format as, i.e in Fig. 2. Following parameters have to be specified :

— *Environment* : fluid density, gravity constant, water-depth and wave reference point. Specify 0. for infinite water depth case.
— *Description of floating bodies* : number of bodies, meshfile's name, number of points and number of panels, number of degrees of freedom, motion description, number of resulting generalized forces and its description.
  — Meshfile has to be specified in the folder projdir/
  — Number of points and panels correspond with the data in the meshfile
  — For each motion and resulting generalized force, 7 parameters have to be specified in a row. First parameter, 1 for translation motion/force, 2 for rotation motion/force. Second to fourth parameters are unit vector of motion/force, 1 0 0 for surge/roll, 0 1 0 for sway/roll, 0 0 1 for heave/yaw. Fifth to seventh parameters are the reference point coordinate (x, y, z).
  — In multibodies case, all the parameters have to be specified in rows for each body.
— *Load case to be solved* : contains wave frequency and wave direction parameter.
  — Four wave frequency parameters have to be specified in a row. First, the frequency type, 1 for radial-frequency [rad/s], 2 for frequency [Hz] and 3 for period [s]. Second to fourth parameter are number of frequency, the minimum and maximum values.
  — The wave direction parameters are number of direction, the minimum and maximum angle directions [deg].
— *Post processing* contain parameters for Impulse Response Functions, pressure, Kochin, free surface elevation, RAO and frequency type output.

```
--- Environment -------------------------------------------------------------------------------------
1025.                   ! RHO           ! KG/M**3    ! Fluid specific volume
9.81                    ! G             ! M/S**2     ! Gravity
0.                      ! DEPTH         ! M      ! Water depth %deep water case
0.   0.                 ! XEFF YEFF     ! M      ! Wave measurement point
--- Description of floating bodies -----------------------------------------------------------------
1                       ! Number of bodies
--- Body 1 -----------------------------------------------------------------------------------------
OC5_cylinder634_Nem.dat                 ! Name of meshfile
638 634                                 ! Number of points and number of panels
6                                       ! Number of degrees of freedom
1 1. 0. 0. 0. 0. 0.                     ! Surge
1 0. 1. 0. 0. 0. 0.                     ! Sway
1 0. 0. 1. 0. 0. 0.                     ! Heave
2 1. 0. 0. 0. 0. 0.000000               ! Roll about a point
2 0. 1. 0. 0. 0. 0.000000               ! Pitch about a point
2 0. 0. 1. 0. 0. 0.000000               ! Yaw about a point
6                                       ! Number of resulting generalised forces
1 1. 0. 0. 0. 0. 0.                     ! Force in x direction
1 0. 1. 0. 0. 0. 0.                     ! Force in y direction
1 0. 0. 1. 0. 0. 0.                     ! Force in z direction
2 1. 0. 0. 0. 0. 0.000000               ! Moment force in x direction about a point
2 0. 1. 0. 0. 0. 0.000000               ! Moment force in y direction about a point
2 0. 0. 1. 0. 0. 0.000000               ! Moment force in z direction about a point
0                                       ! Number of lines of additional information
--- Load cases to be solved ------------------------------------------------------------------------
1 100    0.0628      6.28               ! Freq type 1,2,3=[rad/s,Hz,s], Number of wave frequencies,
1   0.000000    0.000000                ! Number of wave directions, Min and Max (degrees)
--- Post processing --------------------------------------------------------------------------------
0   0.1 10.             ! IRF                   ! IRF calculation (0 for no calculation), time ste
0                       ! Show pressure
0   0.  180.            ! Kochin function        ! Number of directions of calculation (0 for no ca
0   50  400.    400.! Free surface elevation ! Number of points in x direction (0 for no calcut
1                       ! Response Amplitude Operator (RAO), 0 no calculation, 1 calculated
1                       ! output freq type, 1,2,3=[rad/s,Hz,s]
--- QTF---------------------------------------------------------------------------------------------
1                       ! QTF flag, 1 is calculated
65  0.0628 4.082        ! Number of radial frequencies, Min, and Max values for the QTF computation
0                       ! 0 Unidirection, Bidirection 1
2                       ! Contrib, 1 DUOK, 2 DUOK+HASBO, 3 Full QTF (DUOK+HASBO+HASFS+ASYMP)
NA                      ! Name of free surface meshfile (Only for Contrib 3), type 'NA' if not appl
0   0   0               ! Free surface QTF parameters: Re Nre NBessel (for Contrib 3)
0                       ! 1 Includes Hydrostatic terms of the quadratic first order motion, -[K]xi2_
1                       ! For QTFposProc, output freq type, 1,2,3=[rad/s,Hz,s]
1                       ! For QTFposProc, 1 includes DUOK in total QTFs, 0 otherwise
1                       ! For QTFposProc, 1 includes HASBO in total QTFs, 0 otherwise
0                       ! For QTFposProc, 1 includes HASFS+ASYMP in total QTFs, 0 otherwise
----------------------------------------------------------------------------------------------------
```

FIGURE 2 – Nemoh.cal input file

  - The IRFs computation requires 3 parameters ; a switch 0 is not calculated, 1 calculated, a time-step and a maximum time.
  - A switch pressure parameter, 0 is not calculated, 1 calculated.
  - The Kochin parameters are a number of direction (specify 0 if it is not calculated), min and max values angle direction [deg].
  - The free surface parameters are number of point in x direction (specify 0 if it is not calculated) and y direction, dimension of domain in x and y direction [m].
  - A switch for RAO computation, 0 is not calculate and 1 calulated. If QTF will be computed, the RAO has to be computed then the switch has to be 1.
  - Frequency output option : 1 for the radial frequency [rad/s], 2 the frequency [Hz] and period [s].
- *Quadratic Transer Function (QTF)* contains following parameters
  - A switch 1 is calculated and 0 is not calculated. If the switch=1 then the NEMOH1 module produces the source-distribution file for each problem and

saved in /projdir/results/source.

- The frequency parameters are only in radial frequency [rad/s], number of freq, min and max value. The values are not necessarily same as the input in NEMOH 1 but should be in the range as in NEMOH1 input, then an interpolation may be applied.
- A directional switch is 0 for uni-direction and 1 for bi-direction. So in case of the multi-direction is applied in NEMOH1, all the direction interaction will be computed for the bi-direction case. In the uni-direction case, only the same-direction interaction, $\beta_1 = \beta_2$, will be computed.
- Contribution parameter : 1 computes only the quadratic terms of QTFs, DUOK, 2 computes the quadratic and the body force contribution in the potential QTFs, DUOK+HASBO, 3 the computation includes the free-surface integrals in the finite domain and semi-infinite domain, DUOK+HASBO+HASFS+ASYMP.
- If Contrib=3, the a free-surface mesh file name has to be specified and the file is placed in /projdir/mesh. Type NA if it is not applicable, Contrib<3.
- If Contrib=3, specify the free-surface parameters : an external radius, R_e is the maximum radius as in the free-surface mesh, a number of discretized radius points in between the waterline R_b and the external radius, $[R_b, R_e]$, and number of bessel function. The number of bessel function is used in computation in the semi-infinite integral, specify 30 for a default value.
- Switch 1 for adding the quadratic QTF (DUOK) with the Hydrostatic terms of the quadratic first order motion, $-[\boldsymbol{K}]\tilde{\boldsymbol{\xi}}^{(2)}$,where, with z_G is the vertical component of CoG,

$$\tilde{\boldsymbol{\xi}}^{(2)} = [0, 0, z_G(\theta_1^{(1)2} + \theta_2^{(1)2})/2, \theta_2^{(1)}\theta_3^{(1)}/2, -\theta_3^{(1)}\theta_1^{(1)}/2, 0]^T.$$

  Note that this term is optional and need only in QTFsolver. In other software, i.e HYDROSTAR [2] this term is not included.
- Frequency output option : 1 for the radial frequency [rad/s], 2 the frequency [Hz] and period [s].
- In QTFpostproc, QTFs total is calculated with summation of all the terms. Option to exclude/include the terms are available with the corresponding switch for DUOK, HASBO and HASFS+ASYMP terms. Switch 1 to include, 0 to exclude. IF Contrib=2, then HASFS+ASYMP switch has to be 0.

Mesh file : contains all the mesh information with a format as shown in Table 1. Lid panels ($z = 0$) of the structure may be included in this file to switched-on the irregular frequencies removal method.

geomInput file : contain coarse description of mesh, that are number of nodes, number of panels, table of nodes and table of connectivities. The input file has to follow the format as shown in Table 2.

mesh.cal contains mesh and environmental parameters with format as in Table 3. This file is used as input for **mesh** and **hydroCal**. All the parameters are used in **mesh**. Only central of gravity, water density, and gravity are used in **hydroCal**.

input_solver.txt contains solver parameters with format as in Table 4. The parameters are described as follows.

- Number of Gauss Quadrature points, N^2, is used for the surface integration in the influence coefficients. User specifies an integer value of $N \in [1, 4]$.

— Minimum z of flow and source points is defined with a factor eps_zmin multiplied by the maximal horizontal distance between two point of the mesh.
— Three linear-system solvers are available ; 1 Gauss elimination, 2 LU Decomposition, 3 GMRES iterative solver.
— If GMRES solver is chosen then the three parameters, the restart parameter, relative tolerance and maximum iteration, have to be specified. If the tolerance is not achieved after the maximum iteration exceeded then LU decomposition solves the system directly.

Km.dat and *Badd.dat* are additional stiffness matrix and damping coefficient matrix. The files contains the matrix components with size $(Nbody \cdot Nradiation) \times (Nbody \cdot Nradiation)$.

FSmeshfile contains all the free-surface mesh information with a format as shown in Table 5. Quadrilateral panels discretized free-surface area in between the body waterline, R_B, and the exterior radius R_e. Waterline on R_B and R_e has to discretized by line segments.

TABLE 1 – Mesh file format

2	1			First column must be a 2. Second column is 1 if half symmetric body mesh, about (xOz), specified, 0 otherwise.
1	x_1	y_1	z_1	Table of nodes. First column is node ID. Other columns are the node coordinates (x, y, z)
:	:	:	:	All nodes coordinated listed in the rows
0	0.	0.	0.	Last line of table of nodes
1	2	3	4	Table of connectivities. Number of node IDs
:	:	:	:	Connectivities in each panel listed in the rows
0	0	0	0	Last line of table of connectivities

TABLE 2 – geomInput file format

100				Total number of nodes.
25				Total number of panels.
x_1	y_1	z_1		Table of nodes. The node coordinates (x, y, z)
:	:	:		All nodes coordinated listed in the rows
1	2	3	4	Table of connectivities. Number of node IDs
:	:	:	:	Connectivities in each panel listed in the rows

Output files

Hydrostatic output files such as inertia and stiffness matrices are produced by **mesh**, if *geomInput* prescribed, or by **hydroCal**, if *meshfile* prescribed. The files contain the matrix components with size $(Nbody \cdot Nradiation) \times (Nbody \cdot Nradiation)$.

Following hydrodynamics coefficients are produced in tecplot format, which can be open by the Tecplot program or by a text-editor program,

Table 3 – mesh.cal file format

geomInput_name			Name of the geomInput file.
0			1 if a half symmetric body mesh, about (xOz), specified.
0.	0.		Possible translation about x axis (first column) and y axis (second column)
0.	0.	-7	Coordinates of gravity centre
500.			Target for the number of panels in refined mesh
2.			
0.			
1.			
1025			water density (kg/m^3)
9.81			gravity (m/s^2)

Table 4 – input_solver.txt file format

2			Gauss quadrature (GQ) surface integration, N^2 GQ Nodes, specify N=[1,4]
0.001			eps_zmin for determine minimum z of flow and source points of panel.
1			Solver option : 0 GAUSS ELIM., 1 LU DECOMP., 2 GMRES
10	1e-5	1000	GMRES parameters : restart parameter, Rel Tol, max iter

— *FKForce.tec*, *DiffractionForce.tec* and *ExcitationForce.tec* are the output files of the Froude-Krylov, the diffraction and the excitation forces respectively. The output file format is given in Table 6. The file contains the absolute value and the phase [deg] of the force for each frequency, f. The force is given for each specified force axis (i.e. surge, heave, pitch) for each body. The frequency is given based on the chosen freq. type, [rad/s, Hz, s], of the post processing parameter in *Nemoh.cal*, except the Froude-Krylov force is only in the radial frequency [rad/s].

— *RadiationCoefficients.tec* is the output file for added mass and damping coefficients with format as in Table 7. The radiation coefficients are given for each DoF, each force axis and for each frequency. The frequency is given based on the chosen freq. type, [rad/s, Hz, s], of the post processing parameter in *Nemoh.cal.*

The hydrodynamic coefficients are also produced in the *.dat* files, i.e. *CA.dat* for the damping coefficients, *CM.dat* for the added mass coefficients, *Fe.dat* for the excitation force and *FKForce.dat* for the excitation force. The frequency type of the output files is only radial frequency [rad/s]. This output files are used as input files for the QTF module.

RAO.dat is the output file of the response amplitude operator with the file format as in Table. 8. The output file gives the absolute value and the phase of RAO for each degree of freedom and each frequency. The frequency is given based on the chosen freq. type, [rad/s, Hz, s], of the post processing parameter in *Nemoh.cal.* Only radial frequency output file will be produced in the case of the QTF computed.

IRF.tec and *IRF_excForce.tec* are the impulse response functions for the radiation damping and the excitation force, respectively. The radiation damping IRF has the file format as in Table 9 and the excitation force IRF as in Table 10.

Table 5 – Free surface mesh file format

1	5000	4900	400	This row contais the free-surface computation parameters. First column is 1 if half symmetric free surface mesh specified, 0 otherwise. Column 2-4 are Number of points, Number of panels, Number of segmented waterline, respectively.
1	x_1	y_1	z_1	Table of nodes. First column is node ID. Other columns are the node coordinates (x, y, z)
:	:	:	:	All nodes coordinated listed in the rows
0	0.	0.	0.	Last line of table of nodes
1	2	3	4	Table of connectivities in a panel. Number of node IDs
:	:	:	:	Connectivities in each panel listed in the rows
4901	4902			Table of connectivities in a segmented waterline. Number of node IDs
:	:			Connectivities in each line listed in the rows
0	0	0	0	Last line of table of connectivities

pressure.00XXX.dat is a pressure output file for the problem-XXX. Note that the problem number is defined as in order of the diffraction problem ($Nbeta$), the radiation problem ($Ndof$) and for each frequency. So problem-001 is the, first frequency and first wave direction, diffraction problem. Suppose $Nbeta = 1$, then problem-002 is the, first frequency, radiation problem DoF 1. If $Ndof = 6$ then problem-008 is the second frequency diffraction problem. In each file, the absolute value of pressure, $|P|$, (Pa) and the phase, $\angle P$, (rad) are given for each panel. The format of the output file is given in Table 11.

kochin.00XXX.dat is an output file of the kochin function on a prescribed direction for the problem-XXX. In each file, depends on diffraction/radiation problem, the computed absolute value of the Kochin, $|\mathcal{H}|$, and the phase, $\angle\mathcal{H}$, (rad) are saved for each direction,ϑ. The format of the output file is given in Table 12.

freesurface.00XXX.dat is an output file of the free-surface elevation on a prescribed free-surface domain for the problem-XXX. In each file, depends on diffraction/radiation problem, the computed absolute value of the free-surface elevation, $|\eta|$, and the phase, $\angle\eta$, (rad) are saved for each free-surface panel position. The format of the output file is given in Table 13.

OUT_QTFM_N.dat and *OUT_QTFP_N.dat* are the output files of difference- and sum-frequencies QTF. The QTF result are either the total QTF or parts of the QTF terms that depend on the user-choice QTF post-processing parameters in *Nemoh.cal*. The QTF values are given in the absolute value with the phase in deg and real-imaginary parts. The QTF values are normalized by ρg. The frequency type, [rad/s, Hz, s], depends on the user-choice in the *Nemoh.cal*. The format of the output file is given in Table 14. Only the lower triangular part of the QTF matrix, is saved in the file. The full difference-frequency QTF matrix can be constructed with the lower triangular part of the matrix and the upper triangular part which is in conjugate-symmetric with the lower part. The upper triangular part of the sum-frequency QTF is symmetric with the lower triangular part.

Table 6 – Output file format of Froude-Krylov, diffraction and excitation forces

f_1	$\|F_1(f_1)\|$	$\angle F_1(f_1)$	$\cdots$	$\cdots$	$\|F_{Ninteg}(f_1)\|$	$\angle F_{Ninteg}(f_1)$
f_2	$\|F_1(f_2)\|$	$\angle F_1(f_2)$	$\cdots$	$\cdots$	$\|F_{Ninteg}(f_2)\|$	$\angle F_{Ninteg}(f_2)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
f_{Nf}	$\|F_1(f_{Nf})\|$	$\angle F_1(f_{Nf})$	$\cdots$	$\cdots$	$\|F_{Ninteg}(f_{Nf})\|$	$\angle F_{Ninteg}(f_{Nf})$

Table 7 – Output file format of the radiation coefficients

f_1	$M^a_{11}(f_1)$	$B_{11}(f_1)$	$\cdots$	$\cdots$	$M^a_{1Ninteg}(f_1)$	$B_{1Ninteg}(f_1)$
f_2	$M^a_{11}(f_2)$	$B_{11}(f_2)$	$\cdots$	$\cdots$	$M^a_{1Ninteg}(f_2)$	$B_{1Ninteg}(f_2)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
f_{N_f}	$M^a_{11}(f_{N_f})$	$B_{11}(f_{N_f})$	$\cdots$	$\cdots$	$M^a_{1Ninteg}(f_{N_f})$	$B_{1Ninteg}(f_{N_f})$
f_1	$M^a_{21}(f_1)$	$B_{21}(f_1)$	$\cdots$	$\cdots$	$M^a_{2Ninteg}(f_1)$	$B_{2Ninteg}(f_1)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
f_{N_f}	$M^a_{21}(f_{N_f})$	$B_{21}(f_{N_f})$	$\cdots$	$\cdots$	$M^a_{2Ninteg}(f_{N_f})$	$B_{2Ninteg}(f_{N_f})$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
f_{N_f}	$M^a_{N_{DoF}1}(f_{N_f})$	$B_{N_{DoF}1}(f_{N_f})$	$\cdots$	$\cdots$	$M^a_{N_{DoF}Ninteg}(f_{N_f})$	$B_{N_{DoF}Ninteg}(f_{N_f})$

0.4 Test-cases

Folowing test-cases are provided for verification with Aquaplus software,

— 1_Cylinder : half symmetric body mesh, deep water case, wave direction 0°. The results are shown in Fig. 3.

— 2_2Bodies : half symmetric body mesh, two different bodies, water depth 20 m, wave direction 45°. The results are shown in Fig. 4.

— 3_Nonsymmetrical : full non-symmetrical body mesh, deep-water, wave direction 0°. The results are shown in Fig. 5.

— 4_Postprocessing : half symmetric body mesh, water depth 10 m, wave direction 0°. This test-case showing comparison of the free-surface elevation and the kochin function. The results are not shown in this manual. The comparison can be seen using a provided tecplot layout file. Discrepancies of the phase of wave elevation, $\pm\pi/2$, shown between NEMOH and AQUAPLUS due to different convention of the incident potential that may also cause the difference in the kochin function.

Tecplot's layout file *.lay* is provided in each test-cases folder for plotting in Tecplot.

Test-case 5_QuickTest shows quantitative comparison of force and free-surface for the first-frequency diffraction problem. The comparison results are shown in the command window after running the test-case.

Test-case 6_box_coarsemesh is showing procedure for running the code starting with the executable **mesh** with a coarse description mesh file, *meshbox*. No reference data given in this test case.

Following testcase are provided for the QTF verification with HYDROSTAR software [2], the meshes, Fig. 6, are obtained using GMSH,

— 7_QTF_Cylinder : full body mesh with lid panels, CoG $(0, 0, 0)$, deep water, wave

Table 8 – Output file format of *RAO.dat*

f_1	$\|\xi_1(f_1)\|$	$\cdots$	$\|\xi_6(f_1)\|$	$\angle\xi_1(f_1)$	$\cdots$	$\angle\xi_6(f_1)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
f_{N_f}	$\|\xi_1(f_{N_f})\|$	$\cdots$	$\|\xi_6(f_{N_f})\|$	$\angle\xi_1(f_{N_f})$	$\cdots$	$\angle\xi_6(f_{N_f})$

Table 9 – Output file format of *IRF.tec*

t_1	$M^a_{11}(\infty)$	$IRF_{11}(t_1)$	$\cdots$	$\cdots$	$M^a_{1Ninteg}(\infty)$	$IRF_{1Ninteg}(t_1)$
t_2	$M^a_{11}(\infty)$	$IRF_{11}(t_2)$	$\cdots$	$\cdots$	$M^a_{1Ninteg}(\infty)$	$IRF_{1Ninteg}(t_2)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
t_1	$M^a_{21}(\infty)$	$IRF_{21}(t_1)$	$\cdots$	$\cdots$	$M^a_{2Ninteg}(\infty)$	$IRF_{2Ninteg}(t_1)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
t_N	$M^a_{N_{DoF}1}(\infty)$	$IRF_{N_{DoF}1}(t_N)$	$\cdots$	$\cdots$	$M^a_{N_{DoF}Ninteg}(\infty)$	$IRF_{N_{DoF}Ninteg}(t_N)$

direction 0°, the difference-frequency QTF DUOK+HASBO. The results are shown in the density plot, Fig. 7, and in the off-diagonal line plot, Fig. 8.

— 8_QTF_OC4_Semisubmersible : full body mesh with lid panels, CoG $(0, 0, 0)$, water depth 200 m, wave direction 0° and 30°, bi-directional QTF, the difference-frequency QTF DUOK+HASBO. The results are shown in the density plot, Fig. 9 and in the off-diagonal line plot, Fig. 10, of the bi-directional QTF $(\beta_1, \beta_2) = (0°, 30°)$.

— 9a_QTF_SOFTWIND : half symmetric body mesh with lid panels, CoG $(0, 0, -71.56)$, water depth 200 m, wave direction 0° and 30°, bi-directional QTF, the difference-frequency QTF DUOK+HASBO. The results are shown in the density plot, Fig. 11 and in the off-diagonal line plot, Fig. 12, of the bi-directional QTF $(\beta_1, \beta_2) = (0°, 30°)$.

— 9b_QTF_SOFTWIND_FS : half symmetric body mesh without lid panels, half symmetric free-surface mesh, CoG $(0, 0, -71.56)$, water depth 200 m, wave direction 0°, the sum-frequency total QTF DUOK+HASBO+HASFS+ASYMP. The results are shown in the density plot, Fig. 13 and in the off-diagonal line plot, Fig. 14.

Matlab files are provided in the test-case folder for recreating the plots. Comparison of the first-order results between NEMOH and HYDROSTAR for those test-case are also provided in the Matlab file.

Full description of the QTF test-cases results are reported in [8], [9].

Table 10 – Output file format of *IRF_excForce.tec*

t_1	$IRF_1(t_1)$	$\cdots$	$IRF_{Ninteg}(t_1)$
t_2	$IRF_1(t_2)$	$\cdots$	$IRF_{Ninteg}(t_2)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$
t_N	$IRF_1(t_N)$	$\cdots$	$IRF_{Ninteg}(t_N)$

Table 11 – Output file format of *pressure.00XXX.dat*

x_1	y_1	z_1	$\lvert P(\boldsymbol{x}_1)\rvert$	$\angle P(\boldsymbol{x}_1)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
x_{Npanel}	y_{Npanel}	z_{Npanel}	$\lvert P(\boldsymbol{x}_{Npanel})\rvert$	$\angle P(\boldsymbol{x}_{Npanel})$

Table 12 – Output file format of *kochin.00XXX.dat*

ϑ_1	$\lvert\mathcal{H}(\vartheta_1)\rvert$	$\angle\mathcal{H}(\vartheta_1)$
$\vdots$	$\vdots$	$\vdots$
$\vartheta_{N\vartheta}$	$\lvert\mathcal{H}(\vartheta_{N\vartheta})\rvert$	$\angle\mathcal{H}(\vartheta_{N\vartheta})$

Table 13 – Output file format of *freesurface.00XXX.dat*

x_1	y_1	$\lvert\eta(\vec{x}_1)\rvert$	$\angle\eta(\vec{x}_1)$	$Re[\eta(\vec{x}_1)]$	$Im[\eta(\vec{x}_1)]$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
x_{Npanel}	y_{Npanel}	$\lvert\eta(\vec{x}_{Npanel})\rvert$	$\angle\eta(\vec{x}_{Npanel})$	$Re[\eta(\vec{x}_{Npanel})]$	$Im[\eta(\vec{x}_{Npanel})]$

Table 14 – Output file format of *OUT_QTFM_N.dat* and *OUT_QTFP_N.dat*

f_{1_1}	f_{2_1}	β_{1_1}	β_{2_1}	DoF_1	$\lvert QTF\rvert/\rho g$	$\angle QTF$	$Re[QTF]/\rho g$	$Im[QTF]/\rho g$
f_{1_2}	f_{2_1}	β_{1_1}	β_{2_1}	DoF_1	$\lvert QTF\rvert/\rho g$	$\angle QTF$	$Re[QTF]/\rho g$	$Im[QTF]/\rho g$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$f_{1_{Nf}}$	$f_{2_{Nf}}$	$\beta_{1_{Nbeta}}$	$\beta_{2_{Nbeta}}$	DoF_{NDof}	$\lvert QTF\rvert/\rho g$	$\angle QTF$	$Re[QTF]/\rho g$	$Im[QTF]/\rho g$

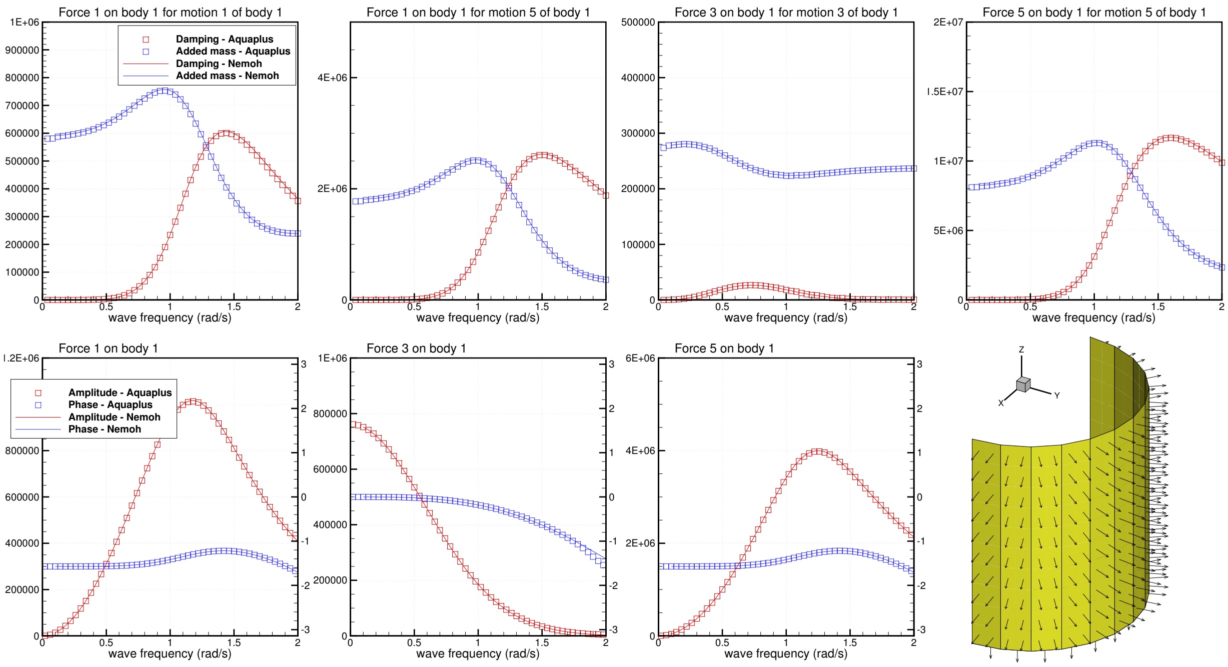

FIGURE 3 – Comparison of the first order results between NEMOH and AQUAPLUS for the testcase 1_Cylinder

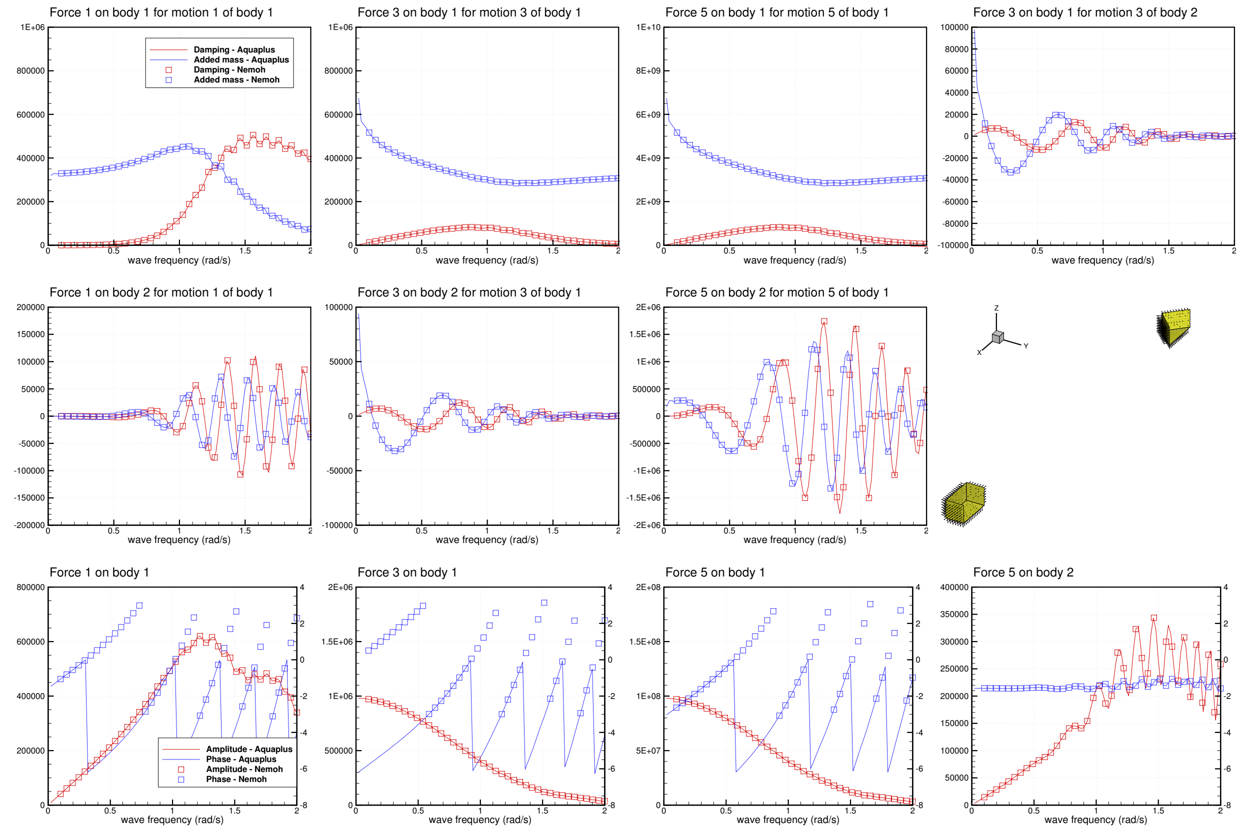

FIGURE 4 – Comparison of the first order results between NEMOH and AQUAPLUS for the testcase 2_2Bodies

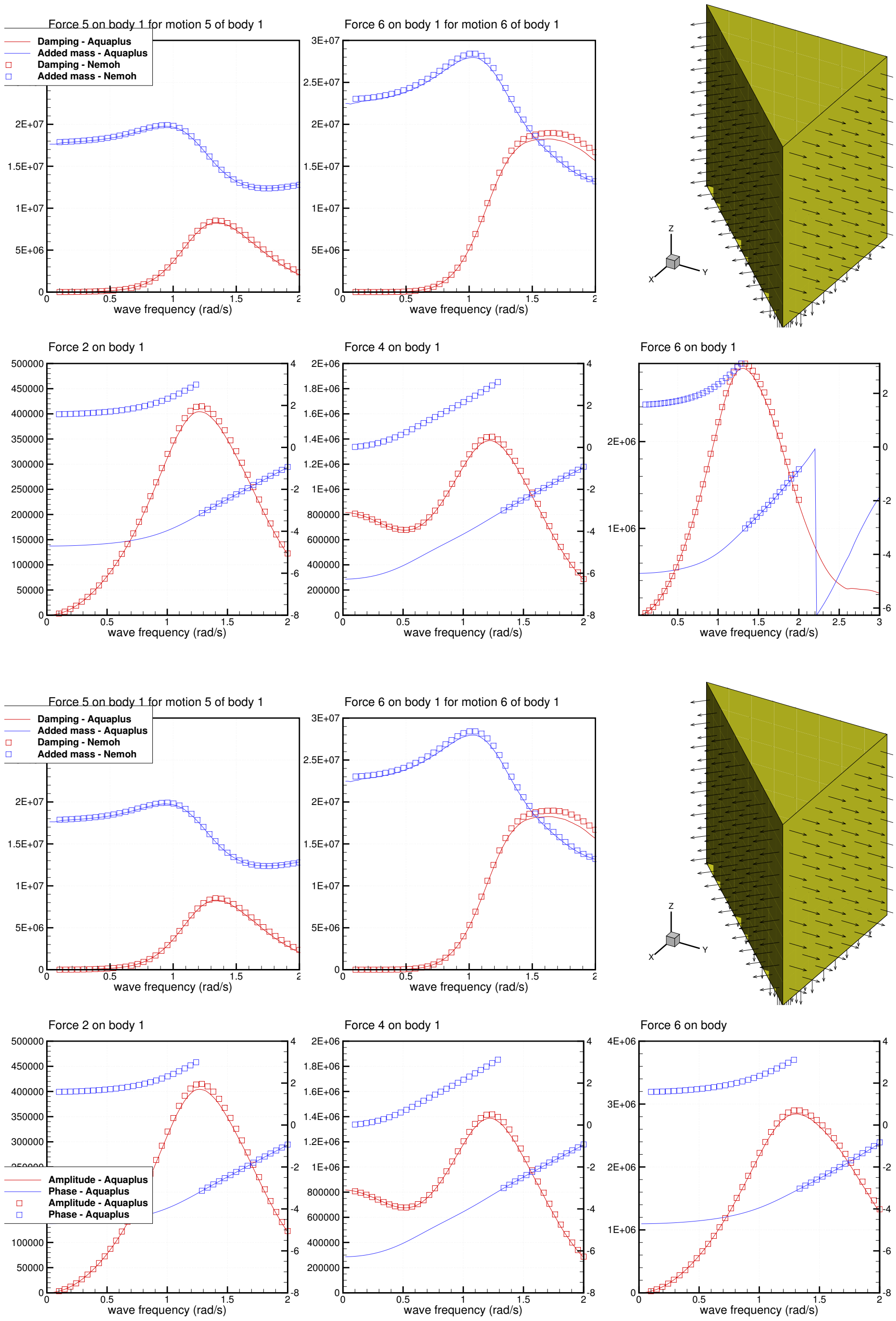

FIGURE 5 – Comparison of the first order results between NEMOH and AQUAPLUS for the testcase 3_Nonsymmetrical

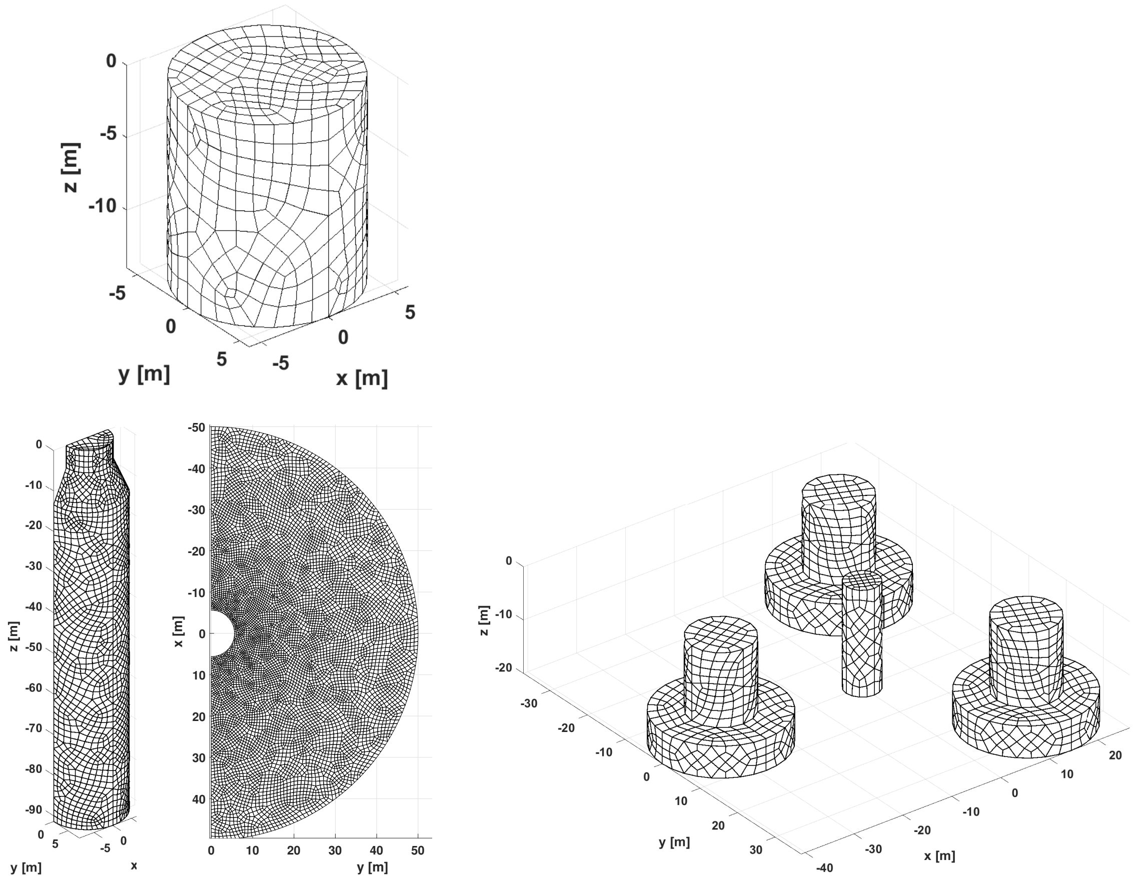

FIGURE 6 – Body boundary mesh for the Cylinder at the top, body boundary mesh and free surface mesh for the SOFTWIND platform, at the bottom left, and body boundary mesh for the OC4-platform, at the bottom right.

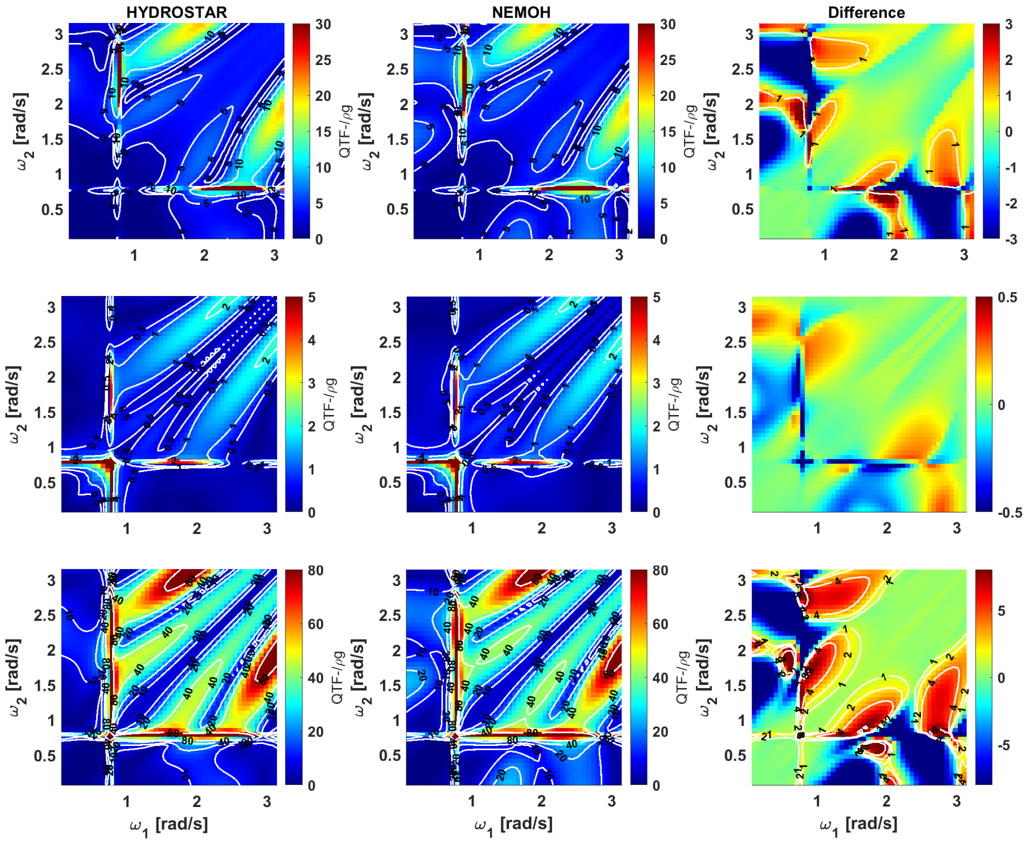

FIGURE 7 – Density plots of the normalized surge difference frequency QTF magnitude (without the free-surface integrals) for the floating Cylinder ; on the top, middle and bottom rows are for surge, heave and pitch, respectively. HYDROSTAR results are on the left column, NEMOH results are on the middle column and the difference on the right column.

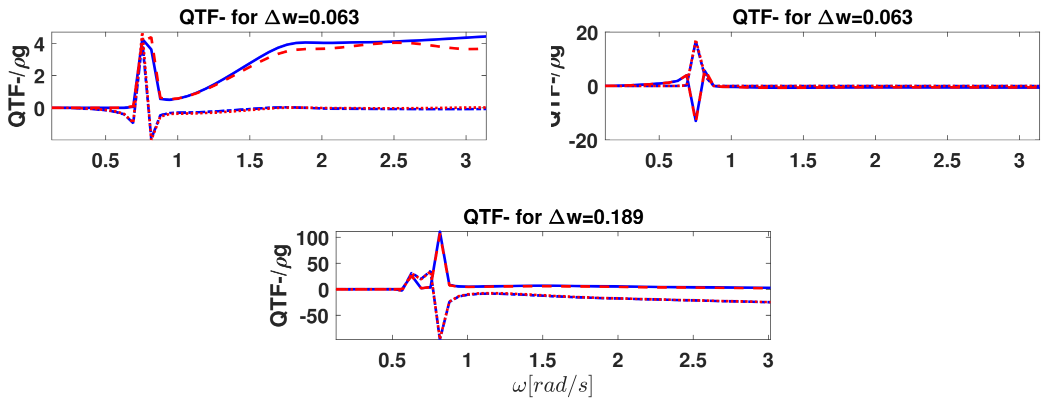

FIGURE 8 – Comparison of the off-diagonal difference frequency QTF for the Cylinder between HYDROSTAR, real part (blue, solid-line), imaginary part (blue, dashed-dot line) and NEMOH, real part (red, dashed-line), imaginary part (red, dotted-line). On the top-left is for surge, on the top-right for heave (the first off-diagonal) and the bottom for pitch (the third off-diagonal)

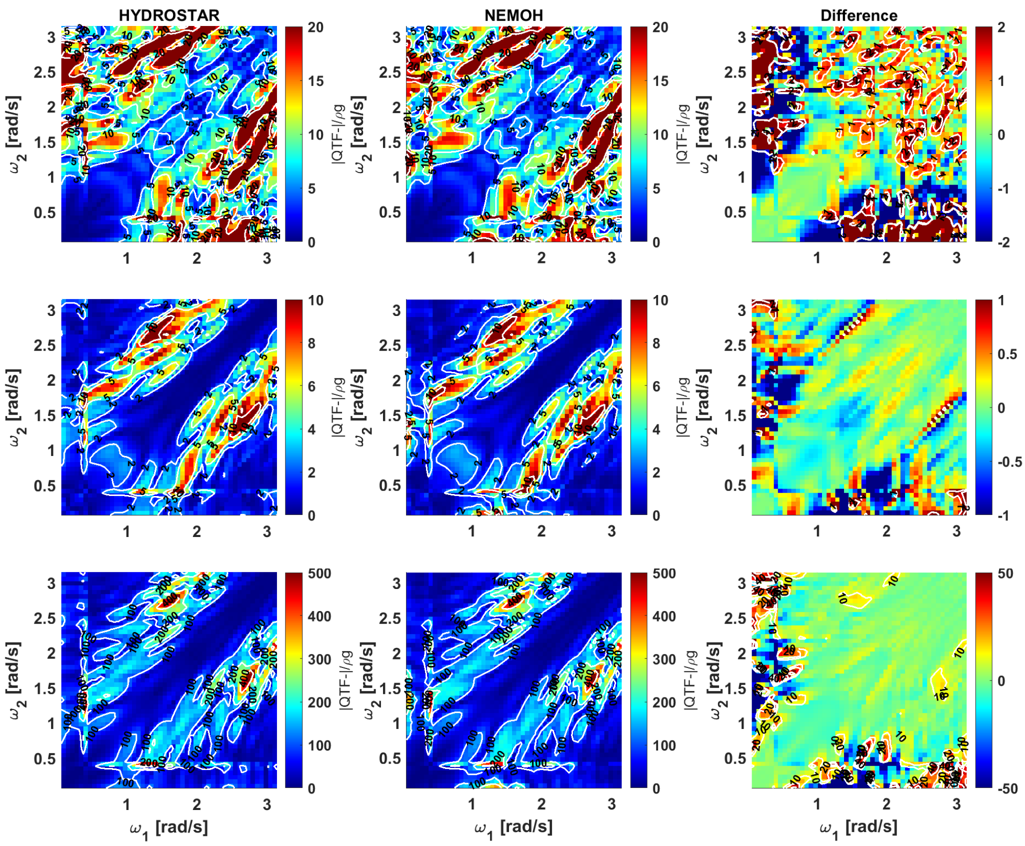

FIGURE 9 – Density plots of the normalized bi-directional, $(\beta_1, \beta_2) = (0°, 30°)$, surge difference frequency QTF magnitude (without the free-surface integrals) for the floating OC4-semisubmersible platform ; on the top, middle and bottom rows are for surge, heave and pitch, respectively. HYDROSTAR results are on the left column, NEMOH results are on the middle column and the difference on the right column.

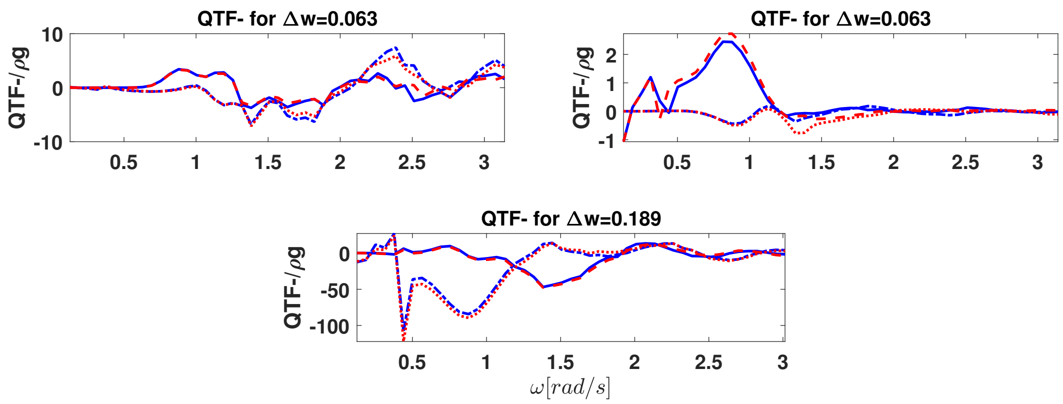

FIGURE 10 – Comparison of the off-diagonal bi-directional, $(\beta_1, \beta_2) = (0°, 30°)$, difference frequency QTF for the OC4-semisubmersible platform between HYDROSTAR, real part (blue, solid-line), imaginary part (blue, dashed-dot line) and NEMOH, real part (red, dashed-line), imaginary part (red, dotted-line). On the top-left is for surge, on the top-right for heave (the first off-diagonal) and the bottom for pitch (the third off-diagonal)

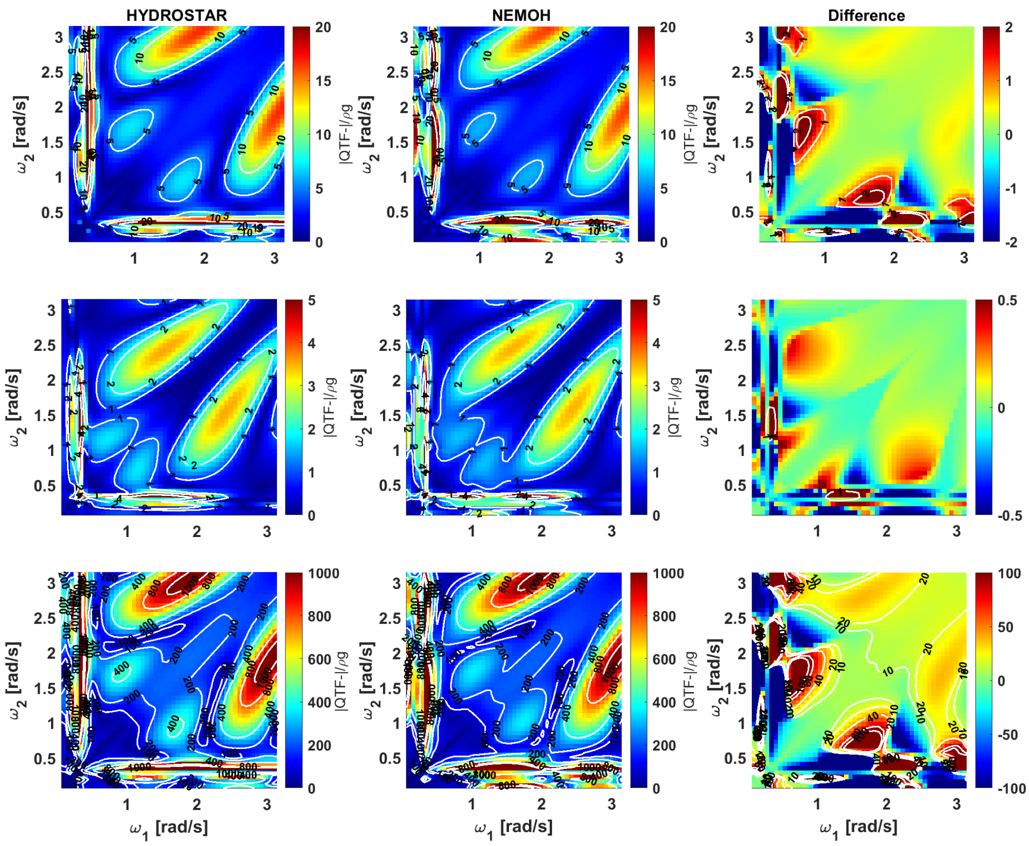

FIGURE 11 – Density plots of the normalized bi-directional, $(\beta_1, \beta_2) = (0°, 30°)$, surge difference frequency QTF magnitude (without the free-surface integrals) for the floating SOFTWIND platform ; on the top, middle and bottom rows are for surge, heave and pitch, respectively. HYDROSTAR results are on the left column, NEMOH results are on the middle column and the difference on the right column.

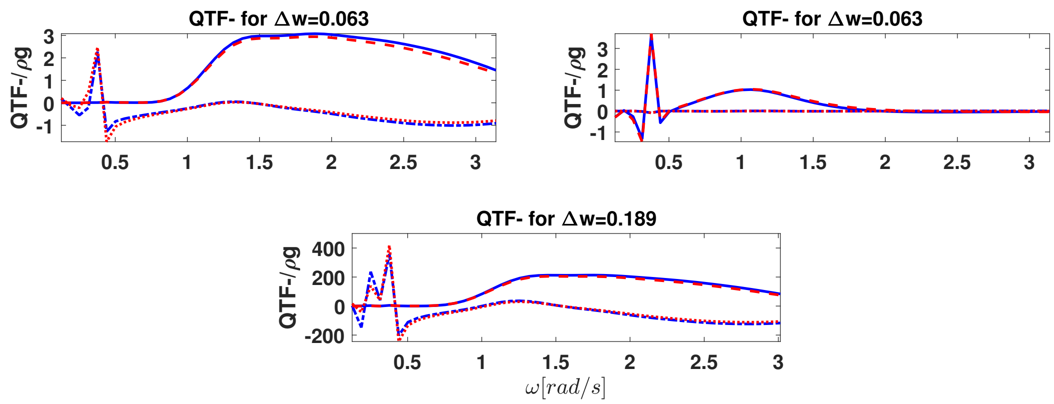

FIGURE 12 – Comparison of the off-diagonal bi-directional, $(\beta_1, \beta_2) = (0°, 30°)$, difference frequency QTF for the SOFTWIND platform between HYDROSTAR, real part (blue, solid-line), imaginary part (blue, dashed-dot line) and NEMOH, real part (red, dashed-line), imaginary part (red, dotted-line). On the top-left is for surge, on the top-right for heave (the first off-diagonal) and the bottom for pitch (the third off-diagonal)

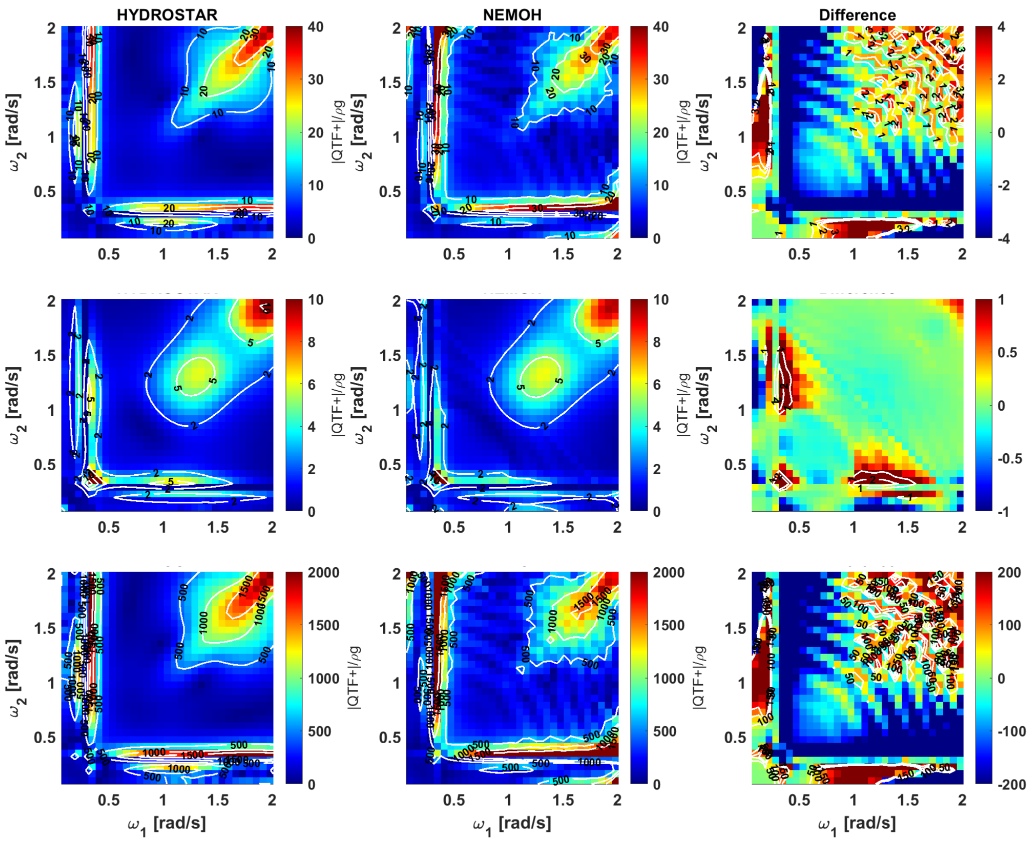

FIGURE 13 – Density plots of the normalized sum-frequency full QTF magnitude (including the free-surface integrals) for the floating SOFTWIND platform ; on the top, middle and bottom row are for surge, heave and pitch, respectively. HYDROSTAR results are on the left column, NEMOH results are on the middle column and the difference in the right column.

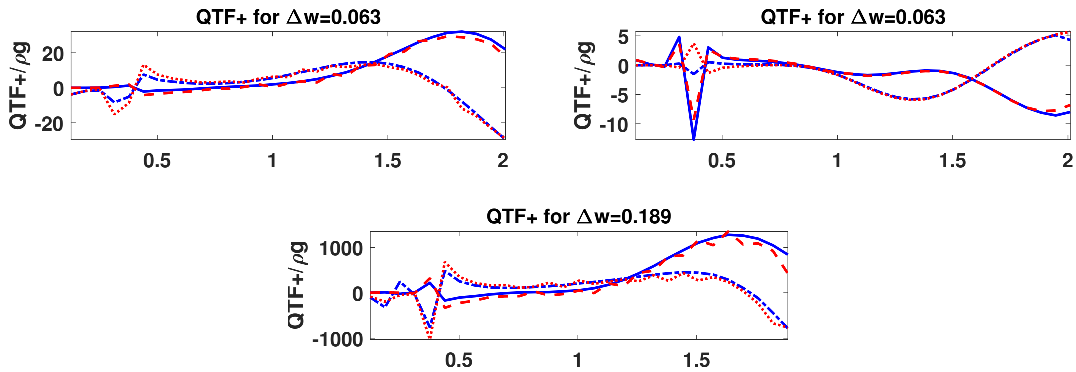

FIGURE 14 – Comparison of the off-diagonal sum-frequency full QTF for SOFTWIND platform between HYDROSTAR, real part (blue, solid-line), imaginary part (blue, dashed-dot line) and NEMOH, real part (red, dashed-line), imaginary part (red, dotted-line). On the top-left is for surge, on the top-right for heave (the first off-diagonal) and the bottom for pitch (the third off-diagonal)

Bibliographie

[1] A. Babarit and G. Delhommeau. Theoretical and numerical aspects of the open source BEM solver NEMOH. In *Proceedings of the 11th European Wave and Tidal Energy Conference*, Sept 2015.

[2] Bureau Veritas. HYDROSTAR Software v8.14, 2020.

[3] Xiao-Bo Chen. *Etudes des réponses du second ordre d'une structure soumise à une houle aléatoire*. PhD Thesis, Université de Nantes, 1988.

[4] G. Delhommeau. Amélioration des performances des codes de calcul de diffraction-radiation au premier ordre. In *Proc. Of 2nd Journées de l'hydrodynamique*, 1989.

[5] Christophe Geuzaine and Jean-François Remacle. GMSH Software v4.8.4, 2021.

[6] B. Molin. Second-order diffraction loads upon three-dimensional bodies. *Applied Ocean Research*, 1(4) :197–202, 1979.

[7] Maxime Philippe, Christophe Peyrard Adrien Combourieu, Fabien Robaux, Gérard Delhommeau, and Aurélien Babarit. Introducing Second Order Low Frequency Loads in the Open-Source Boundary Element Method Code Nemoh. In *Proceedings of the 11th European Wave and Tidal Energy Conference*, Sept 2015.

[8] R. Kurnia, G. Ducrozet. Computation of Second-order Wave Loads on Floating Offshore Wind Turbine Platforms In Bi-chromatic Bi-directional Waves Using Open-Source Potential Flow Solver NEMOH. In *18èmes Journées de l'Hydrodynamique*, 2022.

[9] R. Kurnia, G. Ducrozet, and J.-C. Gilloteaux. Second Order Difference- and Sum-Frequency Wave Loads in the Open-Source Potential Flow Solver NEMOH. In *International Conference on Offshore Mechanics and Arctic Engineering*, volume 5A : Ocean Engineering, 06 2022. V05AT06A019.

[10] V. Frayssé, L. Giraud, S. Gratton, and J. Langou. A set of gmres routines for real and complex arithmetics on high performance computers. Technical Report TR/PA/03/3, CERFACS, 2003.