Grid2Grid : HOS Wrapper Program for CFD solvers

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17 November, 2017

Version 1.0

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1 Introduction

Wave generation solvers using Higher Order Spectral Method (HOS) have been validated and developed for several years (Ducrozet et al. (2016), Ducrozet et al. (2007), Bonnefoy et al. (2011) and Ducrozet et al. (2012)). HOS solves nonlinear wave propagation in open-sea (HOS-Ocean) and also in numerical wave tank (HOS-NWT) with low computation time comparing with other nonlinear wave solvers because the theory is based on pseudo-spectral method (HOS (b) and HOS (a)). Those HOS wave solvers are released as open-source codes, which anyone can develop, use and distribute under the terms of GNU General Public Licence (GPLv3).

Nonlinear irregular wave generation in computational fluids dynamic (CFD) solvers becomes important recently in naval fields to better estimate the loads on offshore structure. The conventional linear superposition methods imply a long computational time for wave generation and the simulation is made almost impossible without having enough computational power. And if the method is based on linear wave theory, there is also question on occurrence of nonlinear phenomenon and the interaction between waves as the simulation goes. Therefore dedicated nonlinear wave solvers with high computational speed are needed.

Grid2Grid is developed as a wrapper program of HOS to generate wave fields from the results of HOS computation. Grid2Grid reconstructs wave fields of HOS with inverse fast Fourier transforms (FFTs) and uses a quick spline module, the nonlinear wave fields can be fastly reconstructed for arbitrary simulation time and space. The nonlinear wave simulation is then possible for a particular position and time where specific nonlinear phenomenon occur.

Grid2Grid compiles a shared library (libGrid2Grid.so) which can be used for communication with other programming language using the ISO_C_BINDING rule. It compiles also a post processing program of HOS.
2 Program Structure

The program structure of Grid2Grid is depicted in Fig. 2.1. The program is composed of several modules (.f90) which are denoted as mod. HOS wave fields are generated by modSurf2Vol from the HOS result file (modes_HOS_SWENSE.dat). Because the results files only contain modes information, the volumic wave fields is reconstructed on HOS grid by inverse FFTs (denoted as $H_2$ Operator). The volumic wave fields in Grid2Grid are called as snapshot of wave fields because it is re-constructed at certain simulation time and grid of HOS. modVol2Vol constructs the interpolation data structure from several snapshot of wave fields by using multidimensional spline module (Williams (2015)). It can directly communicate with other Fortran language. To communicate with other languages, modGrid2Grid can also be used as it receives input data and return wave fields data by using ISO_C_BINDING. modPostGrid2Grid is a post processing module of HOS generating wave fields in VTK format and also wave elevation time series.

![Diagram of Grid2Grid program structure](image)

Figure 2.1. Program Structure of Grid2Grid
The main feature of each module is following.

- **modSurf2Vol**: Wrapper class of HOS-Ocean and HOS-NWT wave fields
- **modVol2Vol**: Interpolation of snapshot of wave fields (multiple Surf2Vol Class)
- **modGrid2Grid**: Communication with other language with ISO_C_BINDING
- **modPostGrid2Grid**: Post processing of HOS (wave fields and wave elevation)
- **modOceanSurf2Vol**: Re-construction HOS-Ocean wave fields
- **modNWTSurf2Vol**: Re-construction HOS-NWT wave fields
- **modFourier_r2c_FFTW**: Wrapper module of FFTW open library
- **modGrid2GridType**: Grid2Grid global variables and auxiliary functions
- **bspline-fortran**: Multidimensional b-spline module written in Fortran.
2.1 typSurf2Vol

2.1.1 Description

Surf2Vol is wrapper class to access HOS Ocean and NWT class. Functionality and data of both HOS classes are similar but the mathematical formulation and meshes are a little bit different. Therefore the flow information from each HOS grid is only taken by using HOS mesh base class and transfer it to Vol2Vol Class. It is reminded that the direct access on the HOS wave fields is only possible by HOS mesh pointer to prevent misuse of HOS wave data.

Surf2Vol class structure is depicted in Fig. 2.2. Surf2Vol class contains HOSOceanSurf2Vol and HOSNWTSurf2Vol classes. When the functionality is called, it calls the functionality of sub-class distinguished by HOS type. When the subroutine correct is called, the sub-class reads HOS modes from HOS result file and conducts $H_2$ operation to re-construct wave fields. Reconstructed wave field is saved on derived HOS grid class. And the HOS grid pointer at Surf2Vol points to derived HOS grid class to access wave fields.

![Surf2Vol class structure](image)

**Figure 2.2.** Surf2Vol class structure
hosNWTSurf2Vol and hosOceanSurf2Vol classes reconstruct HOS wave fields from HOS result file by using the $H_2$ operator. Wave reconstruction and HOS wave theory is well explained in Ducrozet et al. (2007) and Ducrozet et al. (2012). Each class constructs wave fields on derived HOS mesh class which can be pointed by HOS mesh base class.

HOS wave theory is based on the superposition of base modes which satisfy Laplace equation, sea bottom and free surface boundary condition basically, the behavior of the mode function has an exponential profile. This exponential profile could magnify local modes which has high wave number above $z = 0$. For high steepness waves, this property gives unnatural values closed to free surface, criterion to cut local mode is introduced as (2.1).

$$f_{mn}(z) = \begin{cases} \cosh k_{mn}(z + H) & \text{if } f_{mn}(z) < C_f(z) \\ \frac{\cosh k_{mn}H}{C_f(z)} & \text{if } f_{mn}(z) \geq C_f(z) \end{cases}$$

(2.1)

where

- $k_{mn}$: HOS mode wave number
- $z$: HOS z-coordinates
- $H$: water depth
- $C_f(z)$: $f_{mn}(z)$ function criterion value (default = 10)

The parameter $C_f(z)$ is set to the default value of 10 in Grid2Grid. If the local wave velocities generated by Grid2Grid are not sufficient, the parameter can be changed. The parameter is defined in `modGrid2GridType.f90` as a FNZ_VALUE.

HOS result file only contains mode amplitudes computed at each HOS simulation time, the volumic grid should then be reconstructed from those modes. HOS does not need vertical grid information, so z-directional grid information should be given when HOS surf2vol is initialised. Constructed HOS grid is used for interpolation grid.

To construct the HOS grid, following information should be given.

- $zMin, zMax$
- $nZMin, nZMax$
- $nZMinRatio, nZMaxRatio$ [Optional]

where $zMin$ and $zMax$ is used to set z-directional domain and it should have negative and positive value. $nZMin$ and $nZMax$ are the number of z-directional grid. It is recommended to have at least 50-100 points for the interpolation. If a sufficient number of grid points is not given, the interpolation scheme could give strange values due to exponential profile of $f_{mn}(z)$. $nZMinRatio$ and $nZMaxRatio$ are the ratio of maximum and minimum height of grid ($\Delta z_{max}/\Delta z_{min}$). Minimum grid is located at $z = 0$. Those are optional values set to
be 3 as default. The grid can be visualized by using ParaView. The VTK file is located at VTK/Grid2Grid/surf2volMesh.vtk.
2.1.2 Class (Type)

Class : Surf2Vol
- Data :
  - hosNWTSurf2Vol_ : HOS-NWT Surf2Vol Class
  - hosOceanSurf2Vol_ : HOS-Ocean Surf2Vol Class
  - ptrHOSMesh_ : HOS Mesh Pointer

- Functionality :
  - initialize : Initialise HOS Surf2Vol class with HOS type, result file path, ...
  - correct : Update HOS wave fields
  - destroy : Class desroyer

Class : HOSOceanSurf2Vol and HOSNWTSurf2Vol
- Data :
  - HOSfile : HOS result file (modes_HOS_SWENSE.dat)
  - HOSmode : HOS Ocean or NWT modes
  - HOSmesh : HOS Ocean or NWT mesh (Two are different)
  - HOSfftw : HOS FFT class for $H_2$ operator

- Public Functionality :
  - initialize : Initialise HOS Ocean or NWT Surf2Vol with result file path, ...
  - correct : Update HOS Ocean or NWT wave fields
  - destroy : Class desroyer

- Private Functionality :
  - init_read_mod : Read HOS number of modes and allocate dynamic array
  - read_mod : Read HOS modes for given HOS time index
  - buildGlobalMesh : Build HOS mesh with given HOS construction parameter
  - reconstuctionFFTs : Reconstruct wave fields by inverse $H_2$ operator
2.1.3 How to use

- Initialise Surf2Vol

```call```
hosS2V%initialize(hosType, filePath, zMin, zMax, nZmin, nZmax, zMinRatio, zMaxRatio)
```

- Correct Surf2Vol

```call```
hosS2V%correct(hosIndex)
```

- Data access on wave field of Surf2Vol
  - Wave elevation

```call```
eta = hosS2V%ptrHOSMesh_%eta(ix, iy)
```

- Wave velocity

```call```
u = hosS2V%ptrHOSMesh_%eta(ix, iy, iz)
v = hosS2V%ptrHOSMesh_%eta(ix, iy, iz)
w = hosS2V%ptrHOSMesh_%eta(ix, iy, iz)
```

![Image with equations and text](image-url)
○ Dynamic pressure \( p_d = p - \rho g z \)

\[
p_d = \text{hosS2V} \% \text{ptrHOSMesh} \_\% \text{pd}(ix, iy, iz)
\]

- Destruct of Surf2Vol

\[
\text{Call hosS2V} \% \text{destroy}()
\]
2.2 typVol2Vol

2.2.1 Description

Vol2Vol is an interpolation class used to give interpolated wave information data from the reconstructed HOS wave field. It holds several Surf2Vol classes and interpolation class. The Vol2Vol class structure is described in Fig 3.1.

HOS result file holds modes amplitudes time series for the whole HOS simulation time. If we construct HOS wave fields and interpolation data structure for the whole HOS simulation time, not only the computation time is long but also a huge memory is demanded. Grid2Grid aims for construction of demanding wave fields for relatively short period and domain, it is not necessary to construct the whole HOS wave fields and interpolation data structure. Therefore revolving algorithm is applied just to update HOS wave fields adjunct to simulation time and constuct small interpolation data structure for efficient computation time and memory.

When initialize of Vol2Vol is called, it allocates Surf2Vol array, interpolation data and array related to revolving algorithm. And it initialises Surf2Vol classes and interpolation class and call its subroutine correct at $t = 0$.

![Figure 2.3. Vol2Vol class structure](image)
The subroutine \texttt{correct} with input \( t \) first determine HOS Surf2Vol correction index and Surf2Vol order based on input \( t \) and previous HOS time index. By using correction index and order, only necessary HOS Surf2Vol is updated and re-ordered to constructed for interpolation data. After interpolation data is constructed, it is delivered to the interpolation class. The interpolation class communicates with the \texttt{bspline-Fortran} module and constructs the interpolation data structure.

The subroutine \texttt{getEta}, \texttt{getU}, \texttt{getPd} and \texttt{getFlow} return interpolated values for given space and time from the constructed interpolation data structure.

### 2.2.2 Class (Type)

**Class : Vol2Vol**

- **Data**:
  - \( \text{nInterp}_\text{.} \): Interpolation order (2 : Linear, 3 : Quadratic, 4 : Cubic, ... )
  - \( \text{nSaveT}_\text{.} \): Number of Surf2Vol wave fields (\( \text{nSaveT}_\text{.} > \text{nInterp}_\text{.} \))
  - \( \text{HOSs2v}_\text{.}(\cdot) \): Array of Surf2Vol class
  - \( \text{itp2D}_\text{.} \): Interpolation class for 2D waves
  - \( \text{itp3D}_\text{.} \): Interpolation class for 3D waves

- **Functionality**:
  - \( \text{initialize} \): Initialise HOS Vol2Vol class with HOS type, result file path, ...
  - \( \text{correct} \): Update HOS wave fields with real-time
  - \( \text{getEta} \): Get interpolated wave elevation
  - \( \text{getU} \): Get interpolated wave velocity
  - \( \text{getPd} \): Get interpolated dynamic pressure
  - \( \text{getFlow} \): Get flow information
  - \( \text{destroy} \): Class destroyer
2.2.3 How to use

– Initialise Vol2Vol

\begin{verbatim}
Call hosV2V%initialize(hosType, filePath, zMin, zMax, nZmin, nZmax, zMinRatio, zMaxRatio, iflag)
\end{verbatim}

- hosV2V : Vol2vol Class (Type)
- hosType : HOS Type (Ocean or NWT)
- filePath : HOS result file path (modes_HOS_SWENS.dat)
- zMin, zMax : HOS grid z-minimum and z-maximum (vertical domain)
- nZmin, nZmax : Number of z-directional Grid

- zMinRatio, zMaxRatio (Optional)
  : Ratio of maximum and minimum height of grid (default = 3)

- iflag : Writing option (iflag = 1, write Grid2Grid information)

– Correct Vol2Vol

\begin{verbatim}
Call hosV2V%correct(simulTime)
\end{verbatim}

- hosV2V : Vol2vol Class (Type)
- simulTime : Simulation time (real time value)

– Get wave elevation from Vol2Vol

\begin{verbatim}
eta = hosV2V%getEta(x, y, simulTime, iflag)
\end{verbatim}

- hosV2V : Vol2vol Class (Type)
- x, y : x and y position
- simulTime : Simulation time (real time value)

- eta : Wave elevation

- iflag (Optional)
  : if iflag = 1, nondimensional x and y can be given (default = 0).
– Get wave velocity from Vol2Vol

Call hosV2V%getU(x, y, z, simulTime, u, v, w, iflag)

! hosV2V : Vol2vol Class (Type)
! x, y, z : x, y and z position
! simulTime : Simulation time (real time value)
! u, v, z : Wave velocity (x, y, z)
! iflag (Optional)
! : if iflag = 1, nondimensional x and y can be given (default = 0).

– Get dynamic pressure from Vol2Vol

pd = hosV2V%getPd(x, y, z, simulTime, iflag)

! hosV2V : Vol2vol Class (Type)
! x, y, z : x, y and z position
! simulTime : Simulation time (real time value)
! pd : Dynamic velocity (pd = p - rho * g * z)
! iflag (Optional)
! : if iflag = 1, nondimensional x and y can be given (default = 0).

– Get flow information from Vol2Vol

Call hosV2V%getFlow(x, y, z, simulTime, eta, u, v, w, pd, iflag)

! hosV2V : Vol2vol Class (Type)
! x, y, z : x, y and z position
! simulTime : Simulation time (real time value)
! eta : Wave elevation
! u, v, z : Wave velocity (x, y, z)
! pd : Dynamic velocity (pd = p - rho * g * z)
! iflag (Optional)
! : if iflag = 1, nondimensional x and y can be given (default = 0).

– Destroy Vol2Vol

Call hosV2V%destroy()
2.3 modGrid2Grid

2.3.1 Description

modGrid2Grid is not a class but a Fortan module which contains an array of Vol2Vol classes and subroutines to communicate with other languages. The module structure is depicted in Fig. 2.4. It has two static data which are input data array and Vol2Vol array not to have and update multiple Vol2Vol classes for efficiency and to save memory. When Grid2Grid is initialized from a program written in another language, it firstly check the input variables and return HOSIndex. If the same input variables are given, it returns the same HOSIndex and does not allocate nor initialise Vol2Vol. Other languages can distinguish different HOS wave theory by using the HOSIndex. The subroutines correct and get can be called with HOSIndex, position and time.

The array size of modGrid2Grid is 100 by default (It can deal with 100 different HOS waves) but it does not consume much memory because classes of Grid2Grid are programmed with dynamic arrays and consequently only a few of static data are used. If more HOS wave theories are needed, the variable nMaxVol2Vol in src/modGrid2Grid.f90 can be changed to deal with over than 100 different HOS wave theory.

The functionality of modGrid2Grid is almost the same with Vol2Vol.
2.3.2 Subroutines

The interface between other languages with modGrid2Grid will be detailed in Chap. 4. Subroutines in modGrid2Grid follows ISO_C_BINDING.

Static subroutines:

- Initialise Grid2Grid
  - __modgrid2grid_MOD_initializegrid2grid

- Correct Grid2Grid
  - __modgrid2grid_MOD_correctgrid2grid

- Get wave elevation
  - __modgrid2grid_MOD_gethoseta

Figure 2.4. Grid2Grid Module structure
- Get wave velocity
  - \texttt{modgrid2grid.MOD_gethosu}
- Get dynamic pressure
  - \texttt{modgrid2grid.MOD_gethospd}
- Get flow information
  - \texttt{modgrid2grid.MOD_gethosflow}
- Get HOS simulation end time
  - \texttt{modgrid2grid.MOD_gethosendtime}
- Get HOS water depth
  - \texttt{modgrid2grid.MOD_gethoswaterdepth}
- Get logical data indicating HOS wave theory is initialized
  - \texttt{modgrid2grid.MOD_isgrid2gridinitialized}
2.4 PostGrid2Grid

2.4.1 Description

PostGrid2Grid is a HOS post-processing class. It generates 3D VTK files of wave fields for visualization and wave elevation time series computed from Vol2Vol class. Wave fields at desired simulation time and spatial domain and wave elevation time series can be re-generated at some provided wave probes position.

PostGrid2Grid algorithm is depicted in Fig. 2.5. PostGrid2Grid is initialised with input file. The input file postGrid2Grid.inp contains HOS grid information and post processing information. PostGrid2Grid first reads and checks the input file and then build 3D visualization grid and wave probes. Vol2Vol class is also initialised. The subroutine doPostProcessing do time loop of correct. Subroutine correct first corrects the Vol2Vol class and gets the wave fields. If the grid option is set to no air mesh, 3D grid is fitted to wave elevation. It writes the results on files (3D VTK file and wave elevation time series).

![PostGrid2Grid Algorithm](image)

**Figure 2.5.** PostGrid2Grid Algorithm
2.4.2 Class (Type)

Class: PostGrid2Grid

- Data:
  - hosVol2Vol_ : Vol2Vol class
  - rectLGrid_ : Rectangular linear grid for 3D wave fields (VTK output)
  - waveProbe_(:) : Wave probe

- Functionality (Public):
  - initialize : Initialise PostGrid2Grid class
  - correct : Correct Vol2Vol, rectLGrid_ and waveProbe_ and write output
  - writeVTK : Write 3D wave fields in VTK format
  - doPostProcessing : Do post processing
  - destroy : Destructor of PostGrid2Grid class

- Functionality (Private):
  - readPostG2GInputFile : Read PostGrid2Grid input file
  - checkPostG2GParameter : Check PostGrid2Grid input file
  - writeVTKtotalASCII : Write wave fields (Including air domain)
  - writeVTKnoAirASCII : Write wave fields (Grid is fitted to wave elevation)
  - writeWaveProbe : Write wave elevation time series
2.4.3 Input File of PostGrid2Grid

PostGrid2Grid needs input file. The input file name is postGrid2Grid.inp. The input is recognized by keyword. Input file has free format. keyword can be located at any line of file but keyword should be located as first word at line. If special character is added on character, it is recognized as comment. The input keyword is following.

- HOS Type (solver) and Result File (hosFile)

```plaintext
### Select Solver (Ocean or NWT) ----------------------------------- #
solver Ocean
### hosFile Path --------------------------------------------------- #
hosFile modes_HOS_SWENSE.dat
```

- Post Processing Time (startTime, endTime, dt)

```plaintext
### Post Processing Time ------------------------------------------- #
startTime 2712.0
endTime 2812.0
dt 0.1
```

- Write VTK Option (writeVTK) and Air Meshing Option (airMesh)

```plaintext
### Write 3D VTK File (true or false) ------------------------------ #
writeVTK true
### Air Meshing (true or false) ------------------------------------ #
airMesh true
# If airMesh is true or yes, grid will be constructed up to zMax.
# is false or no, mesh will be constructed up to wave
elevation.
```
– 3D Output Domain Size ($x_{\text{Min}}, x_{\text{Max}}, y_{\text{Min}}, y_{\text{Max}}, z_{\text{Min}}, z_{\text{Max}}$)

```plaintext
### 3D Output Domain Size ------------------------------------------ #
xMin 1200
xMax 2000
yMin 1200
yMax 2000
zMin -100.0
zMax 50.0

# zMin and zMax are used to construct Surf2Vol HOS Grid.
```

– Number of Grid ($n_X, n_Y, n_{Z\text{min}}, n_{Z\text{max}}$)

```plaintext
### Number of Mesh for 3D Output ----------------------------------- #
nX 500
nY 500
nZmin 100
nZmax 60

# nZmin and nZmax are used to construct Surf2Vol HOS Grid.
```

– Vertical meshing scheme ($z_{\text{Mesh}}$)

```plaintext
### Z meshing scheme ----------------------------------------------- #
zMesh meshRatio 3.0 3.0

# Meshing Scheme
#
# uniform : uniform grid
# sine : sine spaced grid (densed grid near to $z=0$)
# meshRatio : grid with constant geometric ratio. Minimum dz located
# at $z=0$. (given two ratio is dz_max/dz_min)
# meshRatio needs two ratios (ratio for $z \leq 0$ and ratio for $z > 0$)
```
- Wave probe write option (writeWaveProbe) and Output file path (waveProbeFile)

```plaintext
### Wave probe write option (true or false) ------------------------ #
writeWaveProbe true

### Wave Probe File path ------------------------------------------- #
waveProbeFile waveElevation.dat

# If waveProbeFile is not given in input file.
# Default output file name "waveElevation.dat" is used.
```

- Wave probes

```plaintext
### Wave probe Input Format ---------------------------------------- #
# There should be no blank line after nWaveProbe and probe data.
# If blank line is given, last wave probes will be discarded.
# There should be no blank line.
# ## Format
# nWaveProbe nProbes
# probeName(option) xPos1 yPos1
# probe2Name xPos2 yPos2
# ...
# probeNname xPosN yPosN
#
# ------------------------------ #

### Wave Probe Input ----------------------------------------------- #

nWaveProbe 5
wp1 0.0 0.0
wp2 1.0 2.0
wp3 2.0 3.0
wp4 4.0 5.0
6.0 7.0

# probeName xPosition yPosition
#
# probeName is optional.
```
2.4.4 How to use

Fortran subroutine for postGrid2Grid is given as example.

```fortran
!! Subroutine to run PostGrid2Grid -----------------------------------
Subroutine runPostGrid2Grid(inputFileName)
!! -------------------------------------------------------------------
Use modPostGrid2Grid !! Use PostGrid2Grid Module
!! -------------------------------------------------------------------
Implicit none
Character (Len = * ), intent (in) :: inputFileName !! postGrid2Grid.inp
Type (typPostGrid2Grid) :: postG2G !! postGrid2Grid Class
!! -------------------------------------------------------------------
!! Initialize PostGrid2Grid with Input File
Call postG2G%initialize(inputFileName)
!! Do Post Processing
Call postG2G%doPostProcessing()
!! Destroy
Call postG2G%destroy
!! -------------------------------------------------------------------
End Subroutine
!! -------------------------------------------------------------------
```
3 Installation

3.1 Pre-Install

3.1.1 FFTW Install

Grid2Grid needs fast Fourier transform (FFT) library. FFTW is GNU licenced FFT library. The installation order is the following:

1. Download FFTW library

At the FFTW website [http://www.fftw.org/download.html](http://www.fftw.org/download.html), latest version of FFTW is available. Download FFTW library.

---

**Figure 3.1. Download FFTW library**
2. Extract FFTW library

```bash
$ tar -xvf fftw-3.3.7.tar.gz
```

3. Compile FFTW library

```bash
$ cd fftw-3.3.7/
$ export FFTW_PATH=$PWD
$ ./configure --prefix=$FFTW_PATH
$ make CFLAGS='-fPIC'
$ make install
```

4. Make soft link of FFTW library

If user has super user authority

```bash
$ sudo ln -s $FFTW_PATH/lib/libfftw3.a /usr/local/lib/libfftw3.a
```

If user has no super user authority, third party path in makefile of Grid2Grid can be changed manually. If FFTW library (libfftw3.a) locates at /home/lib/libfftw3.a, then makefile of Grid2Grid can be changed as:

```bash
DTHRDLIB=/home/lib/
```
3.1.2 HOS Ocean and NWT (Optional)

Grid2Grid needs the result file of HOS solver. Installation of HOS is the following:

1. Install FFTW
   See Chapter 3.1.1

2. Install makedepf90

   $ sudo apt-get install makedepf90

3. Install LAPACK

   $ sudo apt-get install liblapack-dev liblapack-doc-man liblapack-doc liblapack-pic liblapack3 liblapack-test liblapack3gf liblapacke liblapacke-dev

4. Download HOS Ocean and NWT

   $ # Path to desired installation path
   $ cd $HOS_INSTALLATION_PATH
   $ git clone https://github.com/LHEEA/HOS-ocean.git
   $ git clone https://github.com/LHEEA/HOS-NWT.git

5. Change shared library path defined in makefile

   Open makefile of HOS Ocean and NWT and change as following:

   #LINKLIB = $(LIBDIR)libfftw3.a $(LIBDIR)liblapack.a $(LIBDIR)librefblas.a
   LINKLIB = $(LIBDIR)libfftw3.a -llapack

   If FFTW is not installed at $(LIBDIR) in makefile, it can be changed as an example of previous chapter.
6. Compile HOS NWT and HOS Ocean

```bash
$ cd HOS-ocean/
$ make
$ cd ../HOS-NWT/
$ make
$ cd ..
```

7. Check executable is generated

```bash
$ # Check HOS NWT
$ ls HOS-NWT/bin/HOS-NWT
$ # Check HOS Ocean
$ ls HOS-ocean/bin/HOS-ocean
```

8. Make soft link (optional)

```bash
$ # Make Soft Link (Optional)
$ export HOS_PATH=$PWD
$ sudo ln -s $HOS_PATH/bin/HOS-NWT /usr/bin/HOS-NWT
$ sudo ln -s $HOS_PATH/bin/HOS-ocean /usr/bin/HOS-ocean
```
3.2 Grid2Grid Installation

3.2.1 Download Grid2Grid

**Download Grid2Grid**

```
$ # Path to desired installation path
$ cd $HOS_INSTALLATION_PATH
$ git clone https://github.com/LHEEA/Grid2Grid.git
```

**Set FFTW Path (FFTW library is not installed on /usr/local/lib/)**

Change DTHRDLIB in makefile at FFTW library path.

```
DTHRDLIB=$FFTW_LIBRARY_PATH

# Example
# DTHRDLIB=/home/lib/ if "libfftw3.a" exists at /home/lib/
```

3.2.2 Compile PostGrid2Grid

```
$ cd Grid2Grid
$ make
```

3.2.3 Compile Grid2Grid Shared Library

**Compile libGrid2Grid.so in Grid2Grid/obj/**

```
$ make createlib
```

**Compile libGrid2Grid.so in $FOAM_USER_LIBBIN**

If OpenFOAM is installed, libGrid2Grid.so can be compiled at $FOAM_USER_LIBBIN. If OpenFOAM environment is called, following make rule can be used directly.

```
$ make createOFlib
```
4 Interface

4.1 GNU and Intel Fortran

An interface example fortran program is included in `interface/fortGrid2Grid`. To communicate with Grid2Grid, the fortran script `modCommG2G.f90` in `interface/fortGrid2Grid` is needed. It is a communication module with `libGrid2Grid.so`. The fortran interface example program is following:

```fortran
!! Program Start ----------------------------------------------------
Program Main
!! ------------------------------------------------------------------
use modCommG2G !! Use Communication Module
!! ------------------------------------------------------------------
Implicit None
!! Variables --------------------------------------------------------
Integer , Parameter :: nChar = 300 !! Default Character Length
Character ( len = nChar ) :: grid2gridPath !! libGrid2Grid.so Path
integer :: hosIndex !! HOS Index
Character ( len = nChar ) :: hosSolver !! HOS Solver (Ocean or NWT)
Character ( len = nChar ) :: hosFileName !! HOS Result File Path
Double precision :: zMin , zMax !! Surf2Vol Domain
integer :: nZmin , nZmax !! Number of vertical grid
Double precision :: zMinRatio , zMaxRatio !! Grading ratio (=3)
Double precision :: t , dt !! Simulation Time, dt
Double precision :: x , y , z !! Computation Point
Double precision :: eta , u , v , w , pd !! HOS Wave Information
!! Dummy variables --------------------------------------------------
integer :: it !! Dummy time loop integer
!! Program Body -----------------------------------------------------
! !... Write Program Start
write (* ,*) "Test program (Connect to Fortran) to use Grid2Grid shared library"

!!!! Set libGrid2Grid.so path.
!!! It is recommended to use absolute path
! grid2gridPath = "/usr/lib/libGrid2Grid.so" (if soft link is made)
grid2gridPath = "/../obj/libGrid2Grid.so"

!!!! Load libGrid2Grid.so and connect subroutines
Call callGrid2Grid(grid2gridPath)

!!!! Declare HOS Index
hosIndex = -1
```
!!!... Set HOS Type (Ocean or NWT)
hosSolver = "NWT"

!!!... Set HOS Result file Path
hosFileName = "modes_HOS_SWENSE.dat"

!!!... Set HOS Surf2Vol Domain and Vertical Grid
zMin = -0.6d0;     zMax = 0.6d0
nZmin = 50;        nZmax = 50
zMinRatio = 3.d0;  zMaxRatio = 3.d0

!! Initialize Grid2Grid and Get HOS Index
Call initializeGrid2Grid(hosSolver, hosFileName, zMin, zMax, nZmin, nZmax, zMinRatio, zMaxRatio, hosIndex)

!! Time Information
t = 0.0d0;     dt = 0.1d0

!! Given Point
x = 0.5d0;     y = 0.5d0;     z = -0.5d0

!! Time Loop
do it = 1,10

!!! Correct HOS Vol2Vol for given time
Call correctGrid2Grid(hosIndex, t)

!! Get Wave Elevation
Call getHOSeta(hosIndex, x, y, t, eta)

!! Get Flow Velocity
Call getHOSU(hosIndex, x, y, z, t, u, v, w)

!! Get Dynamic Pressure
Call getHOSPd(hosIndex, x, y, z, t, pd)

!! Write Flow Information
write(*,*), t, eta, u, v, w, pd

!! Time Update
  t = t + dt
enddo

!! Write End of Program
write(*,*), "Test program (Connect to Fortran) is done ...")
4.2 OpenFOAM

An interface example OpenFOAM program is included in `interface/ofGrid2Grid`. The shared library `libGrid2Grid.so` should be compiled at `$FOAM_USER_LIBBIN`. To check `libGrid2Grid.so` exists at `$FOAM_USER_LIBBIN`, use following shell command:

```
$ ls $FOAM_USER_LIBBIN/libGrid2Grid.so
```

If `libGrid2Grid.so` not exists, refer to Chapter 3.2.

To call shared library `libGrid2Grid.so` in `$FOAM_USER_LIBBIN`, OpenFOAM compiling option is added at `Make`/option. Open `Make`/option and add following compiling option:

```
EXE_LIBS = \
  ... \
  -lgfortran \
  -L$(FOAM_USER_LIBBIN) \
  -lGrid2Grid
```

OpenFOAM interface example program is given next page.
#include "fvCFD.H"

namespace Foam {
    // Grid2Grid Initial Character Length
    const int nCharGridGrid(300);

    // Initialize Grid2Grid Class in Fortran
    // __modgrid2grid_MOD_initializegrid2grid
    // ( 
    //   hosSolver,
    //   hosFileName,
    //   zMin,
    //   zMax,
    //   nZmin,
    //   nZmax,
    //   zMinRatio,
    //   zMaxRatio,
    //   hosIndex
    // )
    // Input
    // hosSolver : "NWT" or "Ocean"
    // hosFileName : filePath of HOS mode result file
    // zMin, zMax : HOS grid zMin and zMax
    // nZmin, nZmax : HOS number of z grid
    // zMinRatio, zMaxRatio : HOS z grid max/min ratio
    // Output
    // hosIndex : HOS Vol2Vol Index
    //
    extern "C" void __modgrid2grid_MOD_initializegrid2grid
    ( const char [nCharGridGrid],
      const char [nCharGridGrid],
      const double*,
      const double*,
      const int*,
      const int*,
      const double*,
      const double*,
      int* )
    ;

    // Correct Grid2Grid for given simulation Time
    // __modgrid2grid_MOD_correctgrid2grid(hosIndex, simulTime)
    // Input
extern "C" void __modgrid2grid_MOD_correctgrid2grid(const int *, const double *);

// - Get HOS Wave Elevation
// _modgrid2grid_MOD_gethoseta (hosIndex, x, y, t, eta)

// Input
// hosIndex : HOS Vol2Vol Index
// x, y, t : (x and y) position and simulation Time (t)

// Output
// eta : wave elevation

extern "C" void __modgrid2grid_MOD_gethoseta(const int *, const double *, const double *, const double *, double *);

// - Get HOS Flow Velocity
// _modgrid2grid_MOD_gethosu (hosIndex, x, y, z, t, u, v, w)

// Input
// hosIndex : HOS Vol2Vol Index
// x, y, z, t : (x, y, z) position and simulation Time (t)

// Output
// u, v, w : (x, y, z) - directional flow velocity

extern "C" void __modgrid2grid_MOD_gethosu(const int *, const double *, const double *, const double *, const double *, double *, double *);
// Get HOS Dynamic Pressure
// __modgrid2grid_MOD_gethospd(hosIndex, x, y, z, t, pd)
// Input
// hosIndex : HOS Vol2Vol Index
// x, y, z, t : (x, y, z) position and simulation Time (t)
// Output
// pd : Dynamic Pressure $p = -\rho \frac{d(\phi)}{dt} - 0.5 \rho |U \cdot U|$
// extern "C" void __modgrid2grid_MOD_gethospd
// (const int *, const double *, const double *, const double *, const double *, double *);

// Get HOS Wave Elevation, Flow Velocity and Dynamic Pressure
// __modgrid2grid_MOD_gethosflow(hosIndex, x, y, z, t, eta, u, v, w, pd)
// Input
// hosIndex : HOS Vol2Vol Index
// x, y, z, t : (x, y, z) position and simulation Time (t)
// Output
// eta : wave elevation
// u, v, w : (x, y, z) - directional flow velocity
// pd : Dynamic Pressure $p = -\rho \frac{d(\phi)}{dt} - 0.5 \rho |U \cdot U|$
// extern "C" void __modgrid2grid_MOD_gethosflow
// (const int *, const double *, const double *, const double *, const double *,
//  double *, double *, double *, double *, double *, double *);

}
/ Main OpenFOAM Program Start
int main(int argc, char *argv[]) {

    // Write Program Start
    Info << "OpenFOAM Program Example to Call Grid2Grid (HOS Wrapper) in OpenFOAM" << endl;

    // Set HOS Solver Type
    const word HOSsolver_("NWT");
    const word HOSFileName_("./modes_HOS_SWENSE.dat");

    // Set File Name
    string strHOSSolver = string(HOSsolver_);
    string strHOSFileName = string(HOSFileName_);

    // Set HOS Solver Type
    const char *HOSsolver = strHOSSolver.c_str();

    // Set HOS Mode Result File Path
    const char *HOSfileName = strHOSFileName.c_str();

    // Set HOS Z Grid Information
    int indexHOS(-1);
    double zMin(-0.6), zMax(0.6);
    int nZmin(50), nZMax(50);
    double zMinRatio(3.0), zMaxRatio(3.0);

    // Initialize Grid2Grid
    __modgrid2grid_MOD_initializegrid2grid(HOSsolver, HOSfileName,
                                           &zMin, &zMax,
                                           &nZmin, &nZMax,
                                           &zMinRatio, &zMaxRatio, &indexHOS);

    Info << "HOS Label : " << indexHOS << endl;

    // Set Position
    double x(0.5), y(0.0), z(-0.5);

    // Define Flow Quantities
    double eta, u, v, w, pd;

    // Set Simulation Time and Time Difference
    double simulTime(0.0);
    double dt(0.1);
// Time Loop
for (int it = 0; it < 11; it++)
{
    // Correct Grid2Grid
    __modgrid2grid_MOD_correctgrid2grid(&indexHOS, &simulTime);

    // Get Wave Eta
    __modgrid2grid_MOD_gethoseta(&indexHOS, &x, &y, &simulTime, &eta);

    // Get Flow Velocity
    __modgrid2grid_MOD_gethosu(&indexHOS, &x, &y, &z, &simulTime, &u, &v, &w);

    // Get Dynamic Pressure
    __modgrid2grid_MOD_gethospd(&indexHOS, &x, &y, &z, &simulTime, &pd);

    Info << " sumulTime : " << simulTime << endl;
    Info << " eta : " << eta << endl;
    Info << " u, v, w : " << u << " " << v << " " << w << endl;
    Info << " pd : " << pd << endl;

    // Get whole Information
    __modgrid2grid_MOD_gethosflow(&indexHOS, &x, &y, &z, &simulTime, &eta, &u, &v, &w, &pd);
    Info << " eta : " << eta << endl;
    Info << " u, v, w : " << u << " " << v << " " << w << endl;
    Info << " pd : " << pd << endl;

    // Time Update
    simulTime += dt;
}
return 0;
5 Validation

foamStar is used to validate Grid2Grid. foamStar is developed by Bureau Veritas and shared with Ecole Centrale de Nantes and it can simulate nonlinear waves, seakeeping problem and also hydro-elasticity problem. It solves multiphase problem with Reynolds Averaged Navier-Stokes equations (RANS) with Volume of fraction (VOF). It is based on standard multiphase solver in OpenFOAM (interDymFoam). To generate waves, foamStar uses explicit blending scheme which blends computed flow values to target values with weight function. The blending function is given as equation (5.1). Some details of foamStar are explained in Seng (2012) and Monroy et al. (2017).

\[ U = (1 - w)U + wU^{target} \]  
\[ \alpha = (1 - w)\alpha + w\alpha^{target} \] (5.1a) (5.1b)

where

\[ w = 1 - (1 - w_{base})^x \]
\[ \chi = \frac{\Delta U \Delta t}{\Delta x} \]
\[ w_{base} = -2\xi^3 + 3\xi^2 \]

By using Grid2Grid, the target values at blending zone can be replaced by the wave components computed from HOS wave theory. For the validation, considered HOS simulation condition is given in Table 5.1.

| Wave Type       | Value | HOS-Ocean | HOS-NWT |
|-----------------|-------|-----------|---------|
|                 |       | 2D  | 3D | 2D | 3D |          |
| Regular Wave    |       | -   | -  | 0.702 | 0.702  |         |
|                 |       | -   | -  | 0.0431 | 0.0288  |         |
| Irregular Waves | \( T_p \) [s] | 0.702 | 1.0 | 1.0 | 0.702 |         |
|                 | \( H_s \) [m] | 0.0288 | 0.10 | 0.05 | 0.0384 |         |
|                 | \( \gamma \) [-] | 3.3 | 3.3 | 3.3 | 3.3 |         |
| Extreme Waves   | \( T_p \) [s] | -   | -  | 17.5 | -     |         |
|                 | \( H_s \) [m] | -   | -  | 15.5 | -     |         |
|                 | \( \gamma \) [-] | -   | -  | 3.3 | -     |         |
5.1 Simulation results

The wave elevation computed by using \texttt{foamStar} and HOS-Ocean are compared in Fig. 5.1. Small differences are observed but it is assumed to be caused by the resolution of the finite volume mesh which is not sufficient near the free surface. The VOF solver gives then those differences. Snapshots of HOS-Ocean wave fields are shown in Fig. 5.1.

The results of HOS-NWT for a two dimensional case is shown in Fig. 5.3. And a simulation snapshot is shown in Fig. 5.4. Three dimensional waves with HOS-NWT are also given in Figs. 5.5 and 5.6.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig51.pdf}
\caption{Comparison of HOS-Ocean wave elevation}
\end{figure}
Figure 5.2. Snapshot of HOS-Ocean wave fields by foamStar
Figure 5.3. Comparison of HOS-NWT 2D wave elevation

Figure 5.4. Snapshot of HOS-NWT 2D wave fields by foamStar
Figure 5.5. Comparison of HOS-NWT 3D wave elevation

Figure 5.6. Snapshot of HOS-NWT 3D wave fields by foamStar
Simulation of extreme waves (1000 year return period waves in Gulf of Mexico (GOM)) (Condition: $H_s = 17.5m$, $T_p = 15.5s$, $\gamma = 3.3$) is simulated with HOS-NWT for 2D cases and used to generate waves in foamStar. The waves are compared with experiments performed in the wave basin of Ecole Centrale de Nantes (ECN). To simulate nonlinear breaking waves, the wave breaking model in HOS is utilized and allows also to capture when wave breaking occur. The expected wave breaking events are shown in Fig. 5.7. In the experiments, wave breaking is observed at the expected position and time by HOS wave theory. The breaking moment in the experiment is shown in Fig. 5.8. The time series of wave elevation measured in the experiments are compared with the results of simulation using Grid2Grid in Fig 5.9. The simulation snapshot when wave breaking occur is shown in Fig. 5.10. The small disturbance at the wave front is observed.

Figure 5.7. Expected wave breaking by HOS

Figure 5.8. Observed wave breaking in experiment
Figure 5.9. Snapshot of HOS-NWT 3D wave fields by foamStar

Figure 5.10. Simulation of wave breaking by foamStar and Grid2Grid
6 Summary

A HOS wrapper program called Grid2Grid is developed for the nonlinear wave simulation of numerical solvers. Most of data and functionality is encapsuled as a class to be easily used and maintained. Grid2Grid generates dynamic linked library as an independent package to be called and easily used in other languages.

The post processing of HOS is also possible by using Grid2Grid. Included post processing program is called postGrid2Grid. The usage is explained in Chapter 2.4.

Grid2Grid is validated by using the code foamStar based on standard multiphase solver of OpenFOAM and also with an experiment. In the experiment, waves corresponding to 1000 year return period in Gulf of Mexico are generated. The wave elevation is measured at the wave breaking position expected by HOS wave theory and compared with the results of the simulation. Good agreement is shown between the measurement and the numerical solutions and the nonlinear wave phenomenon is observed both in experiment and in simulation.

In this document, the Grid2Grid program architecture, class and module structure, principle class data and functionality are explained to understand the feature of Grid2Grid and to be easily applied to numerical solvers. The interface examples with other programming languages are given as a source code and also in Grid2Grid package.
References

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