Explanation of `dynamicRefineFvMesh` for adaptive mesh refinement with an extension for independent bulk and interface mesh refinement for two phase simulations.

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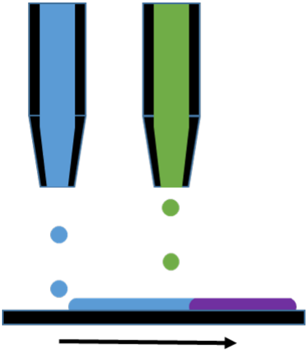
1. Background
2. Using AMR
3. AMR Code
4. Two–Field AMR
5. Tutorial Case

Reactive Inkjet Printing

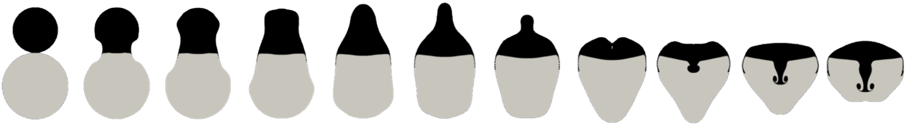
- Additive manufacture (AM) has revolutionised how products can be made.
- However some materials are not fit for AM methods.
- Chemical reactions can be harnessed to created materials on the printing surface.
- The mixing of the chemically reactive droplets is not well understood.



RIJ Example

My Research

- **Project Title**: Mixing dynamics during coalescence of complex fluids.
- Experimentally it is difficult to assess the mixing of droplets.
- Therefore my research is mainly numerical.
- Need an efficient way to capture coalescence and mixing.



Example Simulation of Advective Mixing

Adaptive Mesh Refinement

- Adaptive Mesh Refinement (AMR) is a method of locally adapting the structure of a CFD mesh.
- This can help increase the accuracy of a solution with less significant computational expense.
- Currently OpenFOAM has the functionality to refine in one evolving region, but not two (or more).

My Project

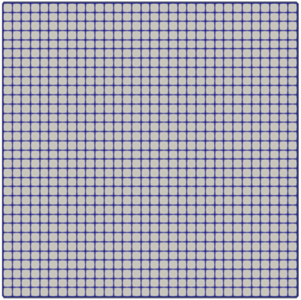
1. Provide a thorough description of the AMR source code.
2. Create a new class capable of refining the mesh for two evolving fields.
3. Extend the unrefinement procedure to add functionality.

Running a simulation with AMR

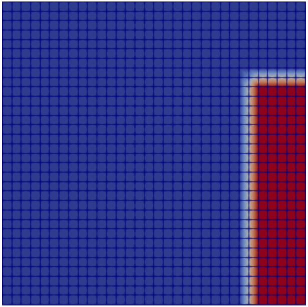
Using the `damBreakWithObstacle` tutorial case we can examine a simulation that uses AMR.

```
cd $FOAM_RUN
cp -r $FOAM_TUTORIALS/multiphase/interFoam/laminar/damBreakWithObstacle .
cd damBreakWithObstacle
./Allrun
```

Initial Conditions

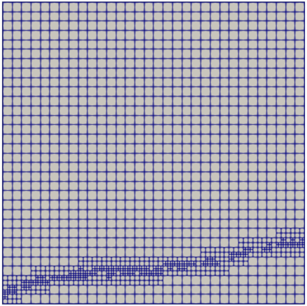


Mesh
uncoloured

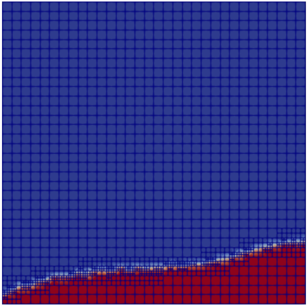


Mesh
coloured by phase fraction

Example Results at Time 0.4 s



Mesh
uncoloured



Mesh
coloured by phase fraction

Case Files

The `damBreakWithObstacle` tutorial contains the following direcotries and files.

```
0
├── U
├── alpha.water
└── p_rgh

constant
├── dynamicMeshDict
├── g
├── momentumTransport
├── polyMesh
└── transportProperties

system
├── blockMeshDict
├── controlDict
├── decomposeParDict
├── fvSchemes
├── fvSolutions
├── setFieldsDict
└── topoSetDict
```

It is the `dynamicMeshDict` that controls the AMR.

The dynamicMeshDict

The dynamicMeshDict contains settings which prescribe and control the mesh refinements.

The dictionary contains the following entries:

- dynamicFvMesh
- refineInterval
- field
- lowerRefineLevel
- upperRefineLevel
- unrefineLevel
- nBufferLayers
- maxRefinemnet
- maxCells
- correctFluxes
- dumpLevel

The dynamicMeshDict

```
dynamicFvMesh   dynamicRefineFvMesh;

// How often to refine
refineInterval  1;

// Field to be refinement on
field           alpha.water;

// Refine field in between lower..upper
lowerRefineLevel 0.001;
upperRefineLevel 0.999;

// If value < unrefineLevel unrefine
unrefineLevel   10;

// Have slower than 2:1 refinement
nBufferLayers   1;

// Refine cells only up to maxRefinement levels
maxRefinement   2;
```

The dynamicMeshDict

```
// Stop refinement if maxCells reached
maxCells        200000;

// Flux field and corresponding velocity field. Fluxes on changed
// faces get recalculated by interpolating the velocity. Use 'none'
// on surfaceScalarFields that do not need to be reinterpolated.
correctFluxes
(
    (phi none)
    (nHatf none)
    (rhoPhi none)
    (alphaPhi0.water none)
    (ghf none)
);

// Write the refinement level as a volScalarField
dumpLevel       true;
```

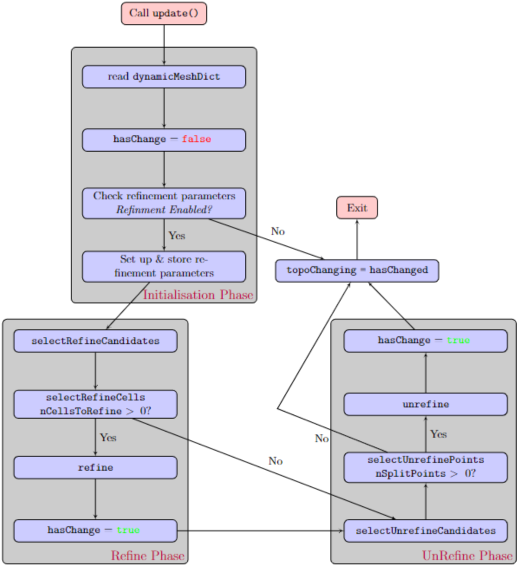
AMR Source Code

- When running the `damBreakWithObstacle` case we only run the `interFoam` solver.
- Within the `interFoam` solver (`interFoam.C`) an object called `mesh` of the `dynamicRefineFvMesh` class is created.
- The CFD mesh is refined by calling the `update` function of the `mesh` object (`mesh.update()` – line 125 of `interFoam.C`).
- The source code for the `dynamicRefineFvMesh` class is found in `$FOAM_SRC/dynamicFvMesh/dynamicRefineFvMesh`.

The update function

There are **three** main sections to the `update` function:

- Initialisation Phase
- Refinement Phase
- Unrefinement Phase



Initialisation Phase

- Mostly concerns creating variables to be used in the latter phases.
- The `dynamicMeshDict` is read and stored as a local dictionary
- The `refineInterval`, `maxCells` and `nBufferLayers` parameters are extracted and checked to ensure they are properly defined.

Initialisation Phase

The dynamicMeshDict is re–read each time–step into the refineDict dictionary.

```
const dictionary refineDict
(
    dynamicMeshDict().optionalSubDict(typeName + "Coeffs")
);
```

Initialisation Phase

For example the `refineInterval` parameter is created and checked by:

```
label refineInterval = refineDict.lookup<label>("refineInterval");

bool hasChanged = false;

if (refineInterval == 0)
{
    topoChanging(hasChanged);

    return false;
}
else if (refineInterval < 0)
{
    FatalErrorInFunction
        << "Illegal refineInterval " << refineInterval << nl
        << "The refineInterval setting in the dynamicMeshDict should"
        << " be >= 1." << nl
        << exit(FatalError);
}
```

In a similar way the `maxCells` and `nBufferLayers` are created and checked.

Refinement Phase

- Cells are selected as candidates to be refined
  - If no cells are to be refined the code moves to the unrefinement phase
- The maximum number of cells that could be refined is calculated
- A list of actual cells to be refined is created.

Refinement Phase

Cells are marked as candidates to be refined using the `selectRefineCandidates` function.

This uses a local `error` function to determine whether to refine a cell

```
scalar err = min(fld[celli] - minLevel, maxLevel - fld[celli]);
```

Notice, cells with a non–zero error value are such that

$$\texttt{minLevel} < \texttt{field} < \texttt{maxLevel}.$$

Refinement Phase

The error value and the `cellLevel` are then used to set the cells that are candidates for refinement:

```
if
(
cellLevel[celli] < maxRefinement
&& cellError[celli] > 0
)
{
candidateCells.set(celli, 1);
```

Refinement Phase

- The number of cells that can be refined without breaking the the `maxCells` limit is calculated assuming each refined cell will cause seven more cells to be created.
- If the number of candidates is larger than `nTotToRefine` then the list of candidates is truncated.
- Else refinement takes place for all the cells.

Unrefinement Phase

- Points are selected as candidates to be removed.
  - If no points are to be removed the code moves to the return statement.
- The points that are marked to be removed are checked to ensure they are not part of any protected areas.
- A list of actual points to be removed is created.

Unrefinement Phase

The unrefinement phase uses the `selectUnrefineCandidates` function to identify points that are to be removed from the mesh. It does this by considering the cells around a point in the mesh.

```
forAll(pointCells(), pointi)
{
    const labelList& pCells = pointCells()[pointi];
    scalar maxVal = -great;
    forAll(pCells, i)
    {
        maxVal = max(maxVal, vFld[pCells[i]]);
    }

    unrefineCandidates[pointi] =
            unrefineCandidates[pointi] && maxVal < unrefineLevel;
}
```

Unrefinement Phase

- After using the `selectUnrefineCandidates` function the candidate points for removal are checked using the `selectUnrefinePoints`.
- It is made sure they do not form part of the cells that have just been refined, or the intermediate layer between refined and unrefined regions of the mesh.
- After this check, if the number of points to be removed from the mesh (`splitPoints`) is non–zero then these points are removed and the mesh is unrefined.

Project Aim

The aim of the adaptations to the source code is to:

- Create a new class capable of refining the mesh for two evolving fields.
- Extend the unrefinement procedure to add functionality.

Method

- Create a new `dynamicDualRefineFvMesh` class by copying the `dynamicRefineFvMesh` class.
- Duplicate the refinement and unrefinement phases so that two evolving regions could be refined on independently.
- Ammend the initialisation phase to ensure that all parameters a checked
- Use the current unrefinement functions as a basis for added unrefinement functionality.

Creation of the `dynamicDualRefineFvMesh` class

A new `dynamicFvMesh` subclass can be created in the following way:

```
cd $WM_PROJECT_USER_DIR
mkdir src/dynamicFvMesh/dynamicDualRefineFvMesh
cd src/dynamicFvMesh/dynamicDualRefineFvMesh
cp -r $FOAM_SRC/dynamicFvMesh/dynamicRefineFvMesh/dynamicRefineFvMesh* .
mv dynamicRefineFvMesh.H dynamicDualRefineFvMesh.H
mv dynamicRefineFvMesh.C dynamicDualRefineFvMesh.C
sed -i 's/dynamicRefineFvMesh/dynamicDualRefineFvMesh/g' dynamicDualRefineFvMesh
    .*
cp -r $FOAM_SRC/dynamicFvMesh/Make .
```

The new class is called `dynamicDualRefineFvMesh` since it will be capable of refining two fields.

Make/files

The Make/files file should read:

```
dynamicDualRefineFvMesh.C

LIB = $(FOAM_USER_LIBBIN)/libdynamicDualRefineFvMesh
```

Make/options

The `Make/options` file should read:

```
EXE_INC = \
 -I$(LIB_SRC)/triSurface/lnInclude \
 -I$(LIB_SRC)/meshTools/lnInclude \
 -I$(LIB_SRC)/dynamicMesh/lnInclude \
 -I$(LIB_SRC)/finiteVolume/lnInclude \
 -I$(LIB_SRC)/dynamicFvMesh/lnInclude

LIB_LIBS = \
 -ltriSurface \
 -lmeshTools \
 -ldynamicMesh \
 -lfiniteVolume \
 -ldynamicFvMesh
```

Method

- Since the `update` function controls the mesh refinement, only this needs to be adapted.
- The reading and refinement for two fields will be added by duplicating the existing code.
- The two refinement fields will be `field1` and `field2` respectively.
- Changes made for one field are similar for the other.
- Adaptations made for one field will be detailed for brevity.

Adaptations to the Initialisation Phase

Recall the reading and checking of the `refineInterval` parameter.

```
label refineInterval = refineDict.lookup<label>("refineInterval");

bool hasChanged = false;

if (refineInterval == 0)
{
    topoChanging(hasChanged);

    return false;
}
else if (refineInterval < 0)
{
    FatalErrorInFunction
        << "Illegal refineInterval " << refineInterval << nl
        << "The refineInterval setting in the dynamicMeshDict should"
        << " be >= 1." << nl
        << exit(FatalError);
}
```

Adaptations to the Initialisation Phase

This is adapted to:

```
label refineInterval1 = refineDict.lookup<label>("refineInterval1");
label refineInterval2 = refineDict.lookup<label>("refineInterval2");

bool hasChanged = false;

if (refineInterval1 == 0 && refineInterval2 == 0)
{
    topoChanging(hasChanged);

    return false;
}
else if (refineInterval1 < 0  || refineInterval2 < 0)
{
    FatalErrorInFunction
        << "Illegal refineInterval " << refineInterval1
        << " | " << refineInterval2 << nl
        << "The refineInterval setting in the dynamicMeshDict should"
        << " be >= 1." << nl
        << exit(FatalError);
}
```

Adaptations to the Refinement Phase

Within the refinement phase (lines 1374–1465 of `dyanmicRefineFvMesh.C`) of the update function, the following variables need to be changed

Original Name	New Name	Type
`refineCells`	`refineCells1`	`PackedBoolList`
`maxRefinement`	`maxRefinement1`	`label`
`selectRefineCandidates`	`selectRefineCandidates1`	`function`
`maxCells`	`maxCells1`	`label`
`nCellsToRefine`	`nCellsToRefine1`	`label`
`cellsToRefine`	`cellsToRefine1`	`labelList`
`nBufferLayers`	`nBufferLayers1`	`label`

Adaptations to the Refinement Phase

Since we have created a new function `selectRefineCandidates1`, this function needs to be declared and defined.

The declaration of the `selectRefineCandidates1` can be added to the `dynamicDualRefineFvMesh.H` file

```
virtual scalar selectRefineCandidates1
(
    PackedBoolList& candidateCell,
    const dictionary& refineDict
) const;
```

Adaptations to the Refinement Phase

The `selectRefineCandidates` function reads some parameters from the `dyanmicMeshDict`:

```
const word fieldName(refineDict.lookup("field"));

 const volScalarField& vFld = lookupObject<volScalarField>(fieldName);

 const scalar lowerRefineLevel =
     refineDict.lookup<scalar>("lowerRefineLevel");
 const scalar upperRefineLevel =
     refineDict.lookup<scalar>("upperRefineLevel");
```

Recall that the `dynamicMeshDict` is locally stored as the `refineDict`

Adaptations to the Refinement Phase

This needs to be amended due to the re–naming of the parameters

```
  const word fieldName(refineDict.lookup("field1"));

   const volScalarField& vFld = lookupObject<volScalarField>(fieldName);

   const scalar lowerRefineLevel =
       refineDict.lookup<scalar>("lowerRefineLevel1");
   const scalar upperRefineLevel =
       refineDict.lookup<scalar>("upperRefineLevel1");
```

Adaptations to the Unrefinement Phase

Within the unrefinement phase (lines 1467–1518 of `dyanmicRefineFvMesh.C`) of the update function, the following variables need to be changed:

Old Name	New Name	Type
`unrefineCandidates`	`unrefineCandidates1`	`boolList`
`selectUnrefineCandidates`	`selectUnrefineCandidates1`	`function`
`pointsToUnrefine`	`pointsToUnrefine1`	`labelList`
`nSplitPoints`	`nSplitPoints1`	`label`
`refineCells`	`refineCells1`	`PackedBoolList`
`unrefineLevel`	`lowerUnrefineLevel`	`label`

Adaptations to the Unrefinement Phase

Again, since we create a new function selectUnrefineCandidates1, this function needs to be declared and defined.

The declaration of the selectUnrefineCandidates1 can be added to the dynamicDualRefineFvMesh.H file

```
void selectUnrefineCandidates1
(
    boolList& unrefineCandidates,
    const dictionary& refineDict
) const;
```

Adaptations to the Unrefinement Phase

- Introduce the `upperRefineLevel` parameter.
- Need to find the minimum value in the cells around a point.
- Then check if this value is larger then `upperRefineLevel`.

Adaptations to the Unrefinement Phase

This process is achieved by the following code:

```
forAll(pointCells(), pointi)
    {
        const labelList& pCells = pointCells()[pointi];
        scalar minVal = great;
        forAll(pCells, i)
        {
            minVal = min(minVal, vFld[pCells[i]]);
        }

        unrefineCandidates[pointi] =
 unrefineCandidates[pointi] && minVal > upperUnrefineLevel
    }
```

Adaptations to the Unrefinement Phase

This addition is added into the existing unrefinement procedure by use of if–statements.

- If both `lowerUnrefineLevel` and `upperUnrefineLevel` are found in the `dynamicMeshDict` then the mesh is unrefined in places in which

$$\texttt{field} < \texttt{lowerUnrefineLevel} \text{ or } \texttt{upperUnrefineLevel} < \texttt{field}$$

- If both only `lowerUnrefineLevel` is found in the `dynamicMeshDict` then the mesh is unrefined in places in which

$$\texttt{field} < \texttt{lowerUnrefineLevel}$$

- If `upperUnrefineLevel` is found in the `dynamicMeshDict` then the mesh is unrefined in places in which

$$\texttt{upperUnrefineLevel} < \texttt{field}$$

damBreak Case

- The same `damBreakWithObstacle` case files will be used to demonstrate the two field refinement capabilites of the `dynamicDualRefineFvMesh`.
- Amendments need to be made to the case files to enable access to the `dynamicDualRefineFvMesh` class.
- Addition parameters need to be specified in the `dynamicMeshDict`.

Case Amendments

Copy a clean version of the `damBreakWithObstacle` Case and allow it to access the `dynamicDualRefineFvMesh` class by:

```
cd $FOAM_RUN
cp -r $FOAM_TUTORIALS/multiphase/interFoam/laminar/damBreakWithObstacle ./
    damBreak
cd damBreak
sed -i 's/dynamicRefineFvMesh/dynamicDualRefineFvMesh/g' constant/
    dynamicMeshDict
echo 'libs ("libdynamicDualRefineFvMesh.so");' >> system/controlDict
```

New dynamicMeshDict

- The `dynamicMeshDict` needs to be changed to account for the two field refinement
- In this tutorial we will prescribe
  - `cellLevel` = 1 refinement in the bulk of the water phase
  - `cellLevel` = 2 refinement on the air–water interface

Interface Refinement Settings

The settings to refine the air–water interface in the `dynamicMeshDict` are given by:

```
// --- Field 1 -- Interface --- //
// How often to refine
refineInterval1 1;
// Field to be refinement on
field1 alpha.water;
// Refine field in between lower..upper
lowerRefineLevel1 0.001;
upperRefineLevel1 0.999;
// If value < unrefineLevel unrefine
lowerUnrefineLevel1 0;
upperUnrefineLevel1 0.9;
// Have slower than 2:1 refinement
nBufferLayers1 2;
// Refine cells only up to maxRefinement levels
maxRefinement1 2;
// Stop refinement if maxCells reached
maxCells1 200000;
```

Bulk Water Refinement Settings

The settings to refine the bulk of the water phase in the `dynamicMeshDict` are given by:

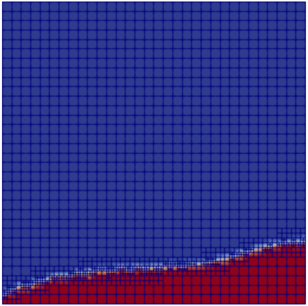
```
// --- Field 2 -- Bulk Water --- //
// How often to refine
refineInterval2 1;
// Field to be refinement on
field2 alpha.water;
// Refine field in between lower..upper
lowerRefineLevel2 0.9;
upperRefineLevel2 1.1;
// If value < unrefineLevel unrefine
lowerUnrefineLevel2 0.001;
// Have slower than 2:1 refinement
nBufferLayers2 1;
// Refine cells only up to maxRefinement levels
maxRefinement2 1;
// Stop refinement if maxCells reached
maxCells2 200000;
```

Running the Case

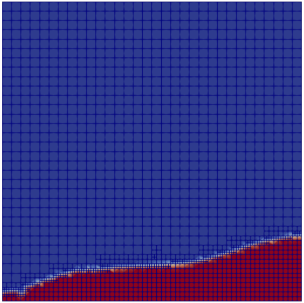
The case can be run by executing:

```
blockMesh
setFields
interFoam
```

Results – 0.4 s



`dynamicRefineFvMesh`



`dynamicDualRefineFvMesh`