CFD using OpenFOAM
Lecture 2: Overview of CFD Methodology

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Outline

Steps Involved

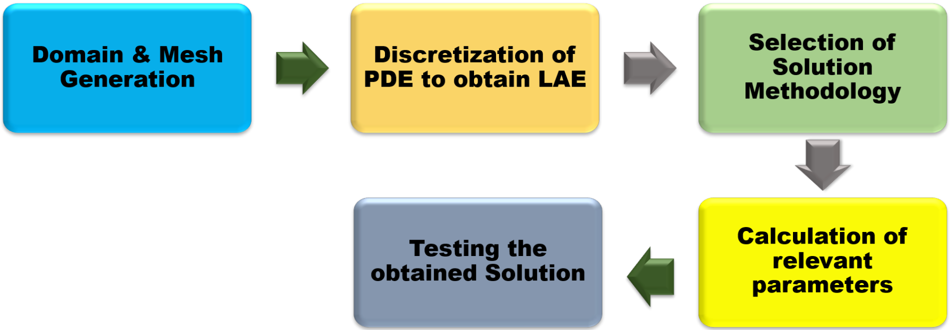
Pre-Processing

PDE to LAE conversion

Solution Scheme

Post-Processing and Testing

- The following flow-chart summarizes the steps involved in CFD Study →



- What is the **area** which you want to capture ?
  (Reasoning: Outside this area, flow features should become normal & not much changes are to observed)

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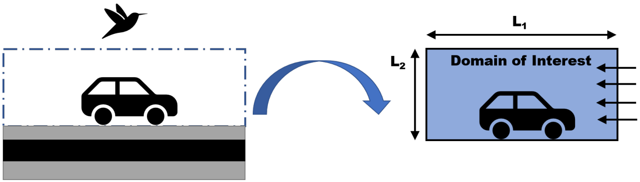

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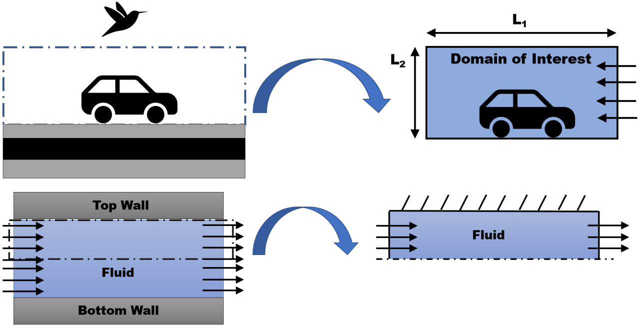

OpenFOAM Geometry Creation

- After installing OpenFOAM, go to tutorial problem
  Eg : openfoam directory/tutorials/incompressible/icoFoam/cavity
- General Structure : Case $\rightarrow$ 0, constant, system
- system $\rightarrow$ **blockMeshDict**

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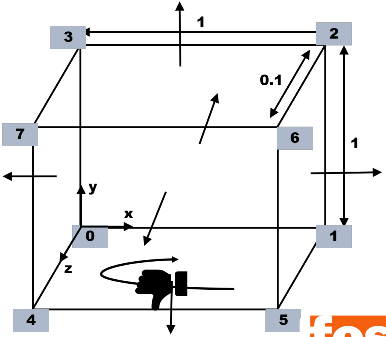
```
vertices
(
    (0 0 0)      // Point 0
    (1 0 0)      // Point 1
    (1 1 0)      // Point 2
    (0 1 0)      // Point 3
    (0 0 0.1)    // Point 4
    (1 0 0.1)    // Point 5
    (1 1 0.1)    // Point 6
    (0 1 0.1)    // Point 7
);
```

```
boundary
(
    movingWall
    {
        type wall;
        faces
        (
            (3 7 6 2)
        );
    }
    fixedWalls
    {
        type wall;
        faces
        (
            (0 4 7 3)
            (2 6 5 1)
            (1 5 4 0)
        );
    }
    frontAndBack
```



- **Video Camera** → colour obtained due to intensity, wavelength of light falling on each pixel of camera.
- **CFD** → colour graphics obtained from solving equations on each pixel (known as control volume/element)

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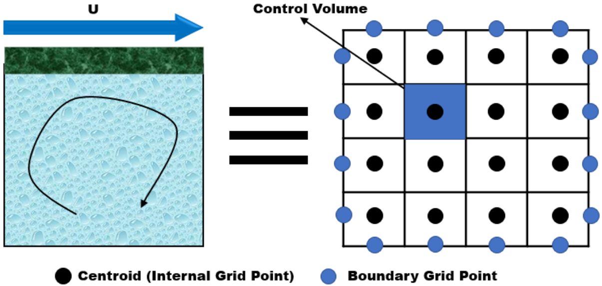
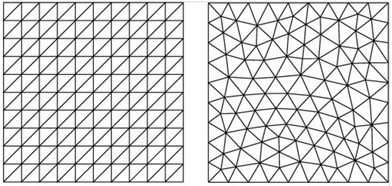


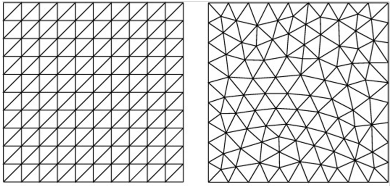
Mesh Generation in OpenFOAM



(a) Structured mesh (b) Unstructured mesh

Two different types of mesh possible for CFD investigation

Ref. Matthew D. Piggott **[2]**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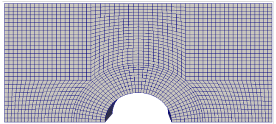
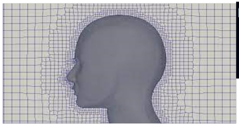
20 CV's in x & y direction


blockMesh with grading


Snappy Hex Mesh

```
blocks
(
    hex (0 1 2 3 4 5 6 7) (20 20 1) simpleGrading (1 1 1)
);
```

Hex block creation **Uniform grid in all directions**

- blockMesh can be generated by first creating block using vertex points of domain and then using SimpleGrading command.

Algebraic Formulation

- After creating Control Volumes (CV) through meshing procedure, we have to solve equations to obtain values of variables.
- But what equations ? can we solve following equation directly on a computer ?

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} \tag{1}$$

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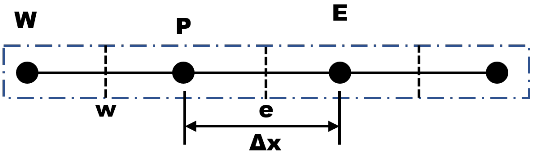
- Can we solve this ? 3x + 2y = 5 ; 6x + 10y = 15

$$\begin{bmatrix} 3 & 2 \\ 6 & 10 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 5 \\ 15 \end{bmatrix} \tag{2}$$

- Objective : Convert Partial Differential Equations (PDE) to Linear Algebraic Equations (LAE).

Consider a one-dimensional domain with 2 internal cells as shown below ; it is intended to solve $\frac{du}{dx} = 3$



1. **Finite Difference Method** : Using Seconnd order central difference scheme

$$\frac{u_E - u_W}{2\Delta x} = 3 \tag{3}$$

2. **Finite Volume Method** : Integrate the PDE over whole C.V as follows :

$$\frac{1}{\Delta V}\iiint_V \frac{du}{dx} dV = \frac{1}{\Delta V}\iiint_V 3dV \tag{4}$$

Apply Gauss-Divergence Theorem to obtain:

$$\int_{CS}\int V dA = 3\Delta V \tag{5}$$

$$(u_e - u_w).1.1 = 3\Delta x.1.1 \tag{6}$$

$$\frac{(u_E - u_W)}{2} = 3\Delta x \tag{7}$$

3. **Finite Element Method** : Divide the domain into small elements (like C.V) and find a solution such that

$$\iiint R.dV = 0 \tag{8}$$

where

$$R = \frac{du_{approximate}}{dx} - 3 \tag{9}$$

W $\rightarrow$ Weight Function.
Find LAE by interpolating 'u' with vertex points of cell

- Once we get some equations, how to solve them ?

$$\begin{bmatrix} 3 & 2 \\ 6 & 10 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} 5 \\ 15 \end{bmatrix} \tag{10}$$

- One Approach : **Direct Method**

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} 3 & 2 \\ 6 & 10 \end{bmatrix}^{-1} \begin{bmatrix} 5 \\ 15 \end{bmatrix} \tag{11}$$

- Second Approach : **Iterative/Indirect Approach**
  Guess an initial value, update it iteratively till difference between iterations is close to zero.

Comparison of Methods and OpenFOAM Implementation

Direct Method	Indirect Method
Gives exact results of LAE	Approximate solution of LAE is obtained
Computationally expensive for large number of variables	Approximate solutions can be obtained with less time
Method is unstable	Solution obtained in all feasible cases
Eg : Direct Inverse, LU decomposition	Eg : Gauss Seidel, Jacobi etc.

OpenFOAM Implementation : Indirect Method using Smooth Gauss Seidel, Conjugate Gradient.

- Now, we are able to calculate Flow variables like velocity, pressure and/or temperature. What next ?
- To understand the effects, usually some scientific/Engineering relevant parameters need to be considered.
- For example : consider flow over aircraft, it is important to know lift force so as decide load that can be carried on aircraft.

$$F_L = \iint_{CS} P(\hat{n}.dA) \tag{12}$$

- In case of flow inside tube, Wall Shear Stress (WSS) needs to be calculated to check the probability of wear and tear of tube walls

$$WSS = -\mu \frac{\partial u_{tangential}}{\partial n} \tag{13}$$

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```
functions
{
    forceCoeffs
    {
    type          forceCoeffs;
    libs ( "libforces.so" );
    writeControl timeStep;
    writeInterval 1;

    patches       ( "cylwall" );
    pName         p;
    UName         U;
    rho           rhoInf;    // Indicates incompressible
    log           true;
    rhoInf        1;         // Redundant for incompressible
    liftDir       (0 1 0);   // Lift Direction
    dragDir       (1 0 0);   // Drag Direction
    CofR          (1.1 0.75 0.05);  // Axle midpoint on ground
    pitchAxis     (0 0 1);
    magUInf       1;        // Velocity
    lRef          0.2;      // Wheelbase length
    Aref          0.02;     // Cross section Area
    }
}
```

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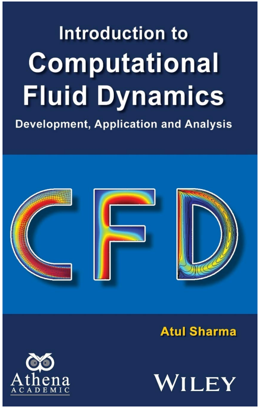
}
```

- On the fly calculation of WSS → after calculations, enter the following command → solverName -postProcess -func wallShearStress

- When a new problem is attempted, it's important to check results for simplified geometry with those available in literature.
- Two Approaches :
  1. **Experimental comparison** : If previous literature contains experimental results, direct comparison can be performed or the experiments can be performed on own
  2. **Other Numerical work** : Comparison can be performed published numerical literature (especially with three-dimensional numerical simulations)
- Summary : Following are steps involved in CFD study
  Geometry (G) $\rightarrow$ Discretization(D) $\rightarrow$ Solution Scheme(S) $\rightarrow$ Post-processing (P) $\rightarrow$ Testing (T)

References

1. Sharma, A. (2016). Introduction to computational fluid dynamics: development, application and analysis. John Wiley & Sons.
2. Hiester, H. R., Piggott, M. D., Farrell, P. E., & Allison, P. A. (2014). Assessment of spurious mixing in adaptive mesh simulations of the two-dimensional lock-exchange. Ocean Modelling, 73, 30-44.
3. https://www.openfoam.com/



Thank you for listening!

Sumant Morab