IMPLICIT LARGE EDDY SIMULATION OF FLOW AND DISPERSION AROUND A BUILDING

Hiroki Ono¹
¹Central Research Institute of Electric Power Industry, Abiko, Japan

ABSTRACT
Validations of Implicit Large Eddy Simulation were carried out about two wind tunnel studies, which are flow and dispersion measurements around the building. Conventional 2nd order scheme was used in anticipation of using unstructured grid CFD code. From the first result, ILES using a TVD scheme could represent an overall flow pattern around the building. From the second result, ILES using a TVD scheme could represent concentration almost within 15%.

INTRODUCTION
Ventilation methods or devices, which use natural wind around buildings, e.g., wind catcher, have become popular with rise of energy saving awareness. It is important to predict unsteady natural wind behaviour accurately to make full use of these devices.

On the other hand, urban space should be well ventilated to avoid stagnation of contaminants. However, it is not easy to avoid stagnation completely especially in existing buildings. From the viewpoint of disaster prevention, an accurately prediction method of unsteady contaminant dispersion is required.

It seems that large eddy simulation (LES) is suitable for prediction method of these unsteady phenomena. Only small-scale motions, which are expected universally, are modelled and large scale motions are directly solved in LES. In many cases, results of LES have better agreement with wind tunnel experiments than Reynolds-averaged Navier-Stokes (RANS) model. Sub-grid scale (SGS) model is important in LES to stabilize numerical calculation as well as to represent an effect of SGS motions to large-scale motions. However, a flow around buildings often has very high Reynolds number. Numerical calculation becomes unstable even if additional viscosity is supplied by SGS model. Generally, numerical unstability is reduced with enough fine grids which has cell based Péclet number lower than 2. However, a grid satisfying that condition is very expensive for prediction of unsteady phenomena with limited time and limited computational resource.

Implicit large eddy simulation (ILES) uses artificial viscosity introduced by upwind-biased convection scheme, instead of SGS viscosity. Second or higher order high-resolution scheme is used for ILES. In spite of having a little systematic explanation, ILES succeeded on high Reynolds number flows in recent years (Grinstein et al., 2007). Some new approaches of ILES are proposed and tested to adapt complex geometries (Hickel et al., 2007; Meyer et al., 2010). On the other hand, applicability of traditional schemes for ILES are examined even in recent years (Bidadi, 2015).

In this paper, two validation works of ILES with schemes that use traditional framework have been carried. One is a wind tunnel experiment of flow around rectangular building. And the other is a wind tunnel experiment of contaminant dispersion under neutral and stable atmospheric stability.

METHODOLOGY
A Navier-Stokes equation and a continuous equation for incompressible flow is shown as follows:

\[ \frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \]  

(1)

\[ \frac{\partial u_i}{\partial x_i} = 0 \]  

(2)

It is not practical to solve these equations directly in high Re number flow. Some coarse graining method is usually used.

Large eddy simulation is one of the coarse graining methods, which uses a low-pass filtering to get rid of high-frequency mode of turbulence. A filtered Navier-Stokes equation and a filtered continuous equation becomes as follows:

\[ \frac{\partial \tilde{u}_i}{\partial t} + u_j \frac{\partial \tilde{u}_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right) \]  

\[ -\frac{\partial}{\partial x_j} (\tilde{u}_i \bar{u}_j - \bar{u}_i \tilde{u}_j) \]  

(3)

\[ \frac{\partial \tilde{u}_i}{\partial x_i} = 0 \]  

(4)

The third term of the right hand side of eq.(3), also called as SGS stress, should be modeled because it cannot be estimated from filtered field values.
Smagorinsky model is very popular as LES closure method, SGS model, for this term.

SGS stress is not modeled explicitly in the ILES. Artificial viscosity introduced from high-resolution schemes for convection term is expected to work as SGS model.

An applicability of lower-order schemes for ILES is tested in this paper because handling 3rd or higher schemes is difficult for general-purpose CFD code, which is based on a finite volume method (FVM). One of the schemes is a 2nd order Total Variation Diminishing (TVD) scheme (Harten, 1983) and the other is a filtered-linear scheme. A convection term of the eq.(3) is expressed as follows in FVM:

\[ \int_{V} \frac{\partial n}{\partial t} dV = \int_{S} \frac{\partial n}{\partial x} n_{i} dS \]  

(5)

V is a volume determined by each cell and S is an area of each surface between two cells. n is a normal vector of the surface S. Now, a value of \( \vec{u}_i \) at the surface S is needed.

Most conventional approach is to take a weighted-average of values on both sides of S. It is a linear-interpolation. Linear interpolation has 2nd order accuracy but usually introduces numerical instability. Most stable approach is upward interpolation. A cell center value of upward side is used for the value of \( \vec{u}_i \) at the surface S. this approach is highly stable, but introduces strong numerical diffusion.

TVD is a non-linear mixture method of linear and upward interpolation. The value of \( \vec{u}_i \) at the surface S of TVD scheme is computed as:

\[ \vec{u}_{i|S}^{TVD} = \vec{u}_{i|S}^{\text{linear}} + \varphi(r)(\vec{u}_{i|S}^{\text{wind}} - \vec{u}_{i|S}^{\text{linear}}) \]  

(6)

\( \varphi(r) \) is a limiter function to avoid a total variation of a whole field increasing. \( r \) is determined with \( \vec{u}_i \) at neighbor cells. In this paper, “limited-Linear” limiter function that is expressed as a simple combination of linear, upward and linear-upward interpolation is used.

The filtered-linear scheme is a pre-set scheme of open source CFD code ‘OpenFOAM’ for LES. The filtered-linear scheme turns into linear interpolation when the solution is smooth. A small amount of upward interpolation is mixed when a staggering solution appears. In this paper, maximum value of \( \theta \) is limited to 0.4.

\[ \vec{u}_{i|S}^{\text{filtered-linear}} = \theta \vec{u}_{i|S}^{\text{wind}} + (1 - \theta) \vec{u}_{i|S}^{\text{linear}} \]  

(6)

All LES and ILES calculations in this paper were carried with OpenFOAM (ver.2.3). Dynamic Smagorinsky model (Lily, 1992) was used for LES and no explicit SGS model was used for ILES. A PISO algorithm (Issa, 1985) was used for pressure-velocity coupling.

**SIMULATION**

Flow around a rectangular building

Wind tunnel experiment of the flow around a rectangular building was carried by CEDVAL project at Hamburg University. An experiment scale was set to 1:200 and approaching flow was adjusted as 1/5th power-law atmospheric boundary layer. The rectangular building has the dimensions of 30m width × 20m depth × 25m height in real scale. The cross section of the wind tunnel is 1.5m width × 1m height.

Fig.1 shows vertical profiles of approaching flow. The approaching flow was driven by driver region with obstacles. Each case almost represented experimental result. ILES-TVD represented mean velocity profile better than LES but underestimated velocity fluctuation.

![Figure 1 Vertical profiles of approaching flow](image_url)

Fig.2 shows vertical profiles of stream-wise mean velocity around the building. Both LES and ILES represented the wind tunnel result at a windward region from the building. The differences between LES and ILES were little in the windward region and above the building within \( x = -50 \) to 0. LES represented the wind tunnel result even in leeward from the building. However, ILES tended to underestimate the mean velocity at 100-150 mm height. It is considered that ILES overestimate a size of circular flow regions at a rooftop of the building and behind the building. Though there were these small disagreements, over all flow pattern was represented by both LES and ILES.

Fig.3 shows vertical profiles of stream-wise velocity fluctuation around the building. Both LES and ILES represented the wind tunnel result at a windward region from the building. LES was also good for above the building. ILES represented well above the building at \( x = 0 \) to 50, although underestimated at \( x = -50 \) to 0. LES and ILES overestimated the velocity fluctuation behind the building. LES had a bit better result than ILES.
Figure 2 Vertical profiles of stream-wise mean velocity around the building (x is a coordinate of stream-wise direction, x = 0 at the center of the building)
Figure 3 Vertical profiles of stream-wise velocity fluctuation around the building (x is a coordinate of stream-wise direction, x = 0 at the center of the building)
Dispersion under neutral and stable atmospheric stability

Measurements of dispersion from rooftop exhaust under two atmospheric stability conditions were carried by Ono et al. An experiment scale was set to 1:500 and approaching flow was adjusted as 1/6th power-law and D and F atmospheric stability class of Pasquill-Gifford chart (Pasquill, 1961 and Gifford, 1961). A simple cubic building was located on the center of the turn-table of the wind tunnel. Tracer gas was emitted by a thin pipe (φ=1.5mm) located on the center of the roof of the cubic building.

Fig. 4 shows vertical profiles of mean concentration behind the building under neutral atmospheric stability. LES represented the wind tunnel result well. ILES-filtered overestimated approximately 30%. ILES-TVD underestimated approximately 15%.

Fig. 5 shows vertical profiles of mean concentration behind the building under stable atmospheric stability. LES represented the wind tunnel result well. ILES-TVD corresponded to LES except near the building. ILES-filtered tended to overestimate.

CONCLUSION

Validations of Implicit Large Eddy Simulation (ILES) with 2nd order convection scheme were carried. From the result, ILES using TVD scheme represented an overall flow pattern well, although the size of circular flow around the building became a bit larger than wind tunnel and LES. ILESs using TVD and filtered-linear scheme were tested on wind tunnel study of atmospheric dispersion. ILES with filtered-linear scheme overestimated mean concentration. In contrast, ILES with TVD scheme underestimated mean concentration, although errors from the wind tunnel result were almost within 15%. It is concluded that ILES with TVD is practical for non-severe condition problem.

In the future work, more suitable scheme for unstructured CFD code will be suggested.

NOMENCLATURE

C = mean concentration
C₀ = mean concentration at the source
H = height of the building
p = pressure
u = velocity
ν = kinematic viscosity

REFERENCES


CEDVAL, Environmental Wind Tunnel Laboratory at Hamburg University, http://www.mi.zmaw.de/index.php?id=433


