INTRODUCTION OF MOMENTUM EQUATIONS IN MICRO-SWIFT

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Abstract: Micro-SWIFT is a Röckle type wind model able to produce very rapidly a mass consistent 3D approximation of the wind flow in a build-up area. Nonetheless, for some specific applications, like very detailed computations around buildings of interest, the ability to strictly respect momentum conservation is necessary. A fast solving momentum equation has been introduced in Micro -SWIFT, called Micro-SWIFT-M. The momentum equation is solved using artificial compressibility technique in steady state situation. Rapidity of the momentum solver is also fostered by simplified turbulence closure and regularity of the horizontal mesh.
Results are presented both on academic test cases and within Paris area. Micro-SWIFT-M simulations are compared with experimental measurements and Code_Saturne CFD wind fields. CPU comparisons are also performed.

Key words: *urban scale, Micro SWIFT, Röckle model, momentum equation, pressure calculation, fast solver, CFD.*

INTRODUCTION

SWIFT is a very fast mass consistent wind model. It produces mass consistent 3D wind fields from a set of sparse wind measurements or larger scale model outputs. Its range of application has been extended to local scale build-up areas using Röckle type parameterisation for buildings. SWIFT is referred as Micro-SWIFT for such applications. Micro-SWIFT interpolates available meteorological data in 3D and creates analytical zones attached to various buildings, such as displacement, cavity, wake or skimming. Mass consistency is finally applied to obtain a divergence free wind field. Micro-SWIFT can be used in conjunction with the Lagrangian Particle Dispersion model SPRAY (Tinarelli et al., 2013, Tinarelli et al, 94). The modelling system is called MSS, Micro-SWIFT-SPRAY (Moussafir et al., 2004, Tinarelli et al., 2007), and is designed to model transport and dispersion of pollutants at local scale in build-up environment, ranging from industrial facilities to city centres.

SWIFT / Micro SWIFT capability can be used on a downscaling mode, called nested simulation, either in stand alone or inside MSS suite: a calculation can be performed from meso scale down to urban local scale. Both meteorological and turbulence data are downscaled by SWIFT, while SPRAY compute transport and dispersion over multiple nested meteorological domains. One particular application of SWIFT nested simulations is industrial incident or malevolent / terrorist activities that may result in the atmospheric dispersion of noxious gases or particles. Parallel version of MSS has been developed to allow for operational handling of large build-up areas such as Paris (Oldrini et al., 2011). In this context, infiltration of contaminant in specific buildings used by general public is foremost. For simple shapes, SWIFT can derive a surface pressure diagnosis that is used with infiltration models such as CONTAM. Nonetheless such buildings can have very complex shapes. In order to get more realistic pressure field on facades for infiltration, momentum equations were added to SWIFT / Micro-SWIFT, with the constraint to keep low CPU time.

The first section will describe the methodology retained in order to integrate momentum equation and turbulence closure inside SWIFT / Micro-SWIFT. Results on academic test cases illustrate quality of results and rapidity of computations. Performances are also evaluated on realistic cases within Paris area, such as Gare du Nord.

IMPLEMENTATION OF A FAST MOMENTUM SOLVER

Equations of motion

For simplicity purposes, Cartesian (x,y,z) coordinates are designed through the use of indexes (1,2,3), and Einstein summation convention on multiple indexes held. The set of equations solved are the Reynolds averaged Navier Stokes equations for the momentum, and the mass conservation for incompressibility:

$$\partial_t U_i = - \partial_j (U_i U_j) – 1/\rho \partial_i P + \partial_j [\nu (\partial_i U_j + \partial_j U_i) + R_{ij})]$$
$$\partial_i U_i = 0$$

Where U is the wind speed, P the pressure, ρ the density, ν the kinematic viscosity and R the turbulent Reynolds stress tensor.

Equations retained in SWIFT-M

We restrain ourselves to steady state solution. The time derivative is only retained to reach steady state.

The turbulent Reynolds stress tensor is modelled through the use of zero-order closure based on mixing length theory. The mixing length is defined through the von Karman constant κ and the distance to solid boundaries d_b as:

$$l_{mix} = \kappa d_b$$

Turbulent kinematic viscosity is then modelled by:

$$\nu_t = l_{mix}^2 \sqrt{(S_{ij} S_{ij})}$$

With S being the deformation tensor defined as $S_{ij} = 1/2 (\partial_i U_j + \partial_j U_i)$

The momentum equation finally becomes:

$$\partial_t U_i = - \partial_j (U_i U_j) – 1/\rho \partial_i P + \partial_j [(\nu + \nu_t) (\partial_i U_j + \partial_j U_i)] \qquad (1)$$

Following (Gowardhan et al, 2011) the continuity equation is modified using the artificial compressibility (AC) method. An artificial speed β for pressure waves is introduced in the continuity equation:

$$1 / \beta \partial_\tau P = = - \partial_i U_i \qquad (2)$$

During transient steps, incompressibility is not verified. But when the pressure reaches steady state, the AC equation reduces to the continuity equation.

Change in coordinates

SWIFT / Micro SWIFT uses terrain following coordinates. Cartesian (x,y,z) coordinates are changed to (X,Y,s) defined as:

$$X = x \text{ and } Y = y$$
$$s = (H – z) / (H – z_g)$$

With H the altitude of the domain top and $z_g(x,y)$ the altitude of the ground (terrain elevation). Hence $s = 0$ is the domain top, whereas $s = 1$ defines the ground.

Partial derivatives in Cartesian and conformal spaces are related in the following way:

$$\partial_x[] = \partial_X[] – s \partial_x h / h \ \partial_s[]$$
$$\partial_y[] = \partial_Y[] – s \partial_y h / h \ \partial_s[]$$
$$\partial_z[] = -1 / h \ \partial_s[]$$

With the domain depth h defined as $h = H – z_g$

Discretisation and numerical scheme

Equation of momentum and pressure are solved using a fractional step technique to move from time steps t_n and t_{n-1} to t_{n+1}:

- First a second order accurate Adams-Bashforth scheme is used to upgrade from $U(t_n)$ and $U(t_{n-1})$ to U* using only the advection-diffusion part of equation (1),
- Then pressure is updated during the wind time step using artificial compressibility,
- Finally U* is upgraded with pressure gradients to get $U(t_{n+1})$

Spatial derivatives are using second order accurate central differencing, except for the advection part where upwind differencing is used.

SIMULATION RESULTS

Academic cases:

Two academic cases have been used to evaluate performances of Micro-SWIFT-M:

- Rectangular building taken from CEDVAL online wind tunnel database of the Hamburg University. Case reference number is A1-1,
- Michelstadt wind tunnel experiment (Berbekar et al, 2013) performed in the framework of COST ES1006 (www.elizas.eu) action. This experiment provides both wind and dispersion measurements for several wind directions and source locations.

Building dimensions of CEVDAL test case are 20m × 30 m × 25m (full scale) in x×y×z axis (wind is along x axis). The reference speed at building top level is 4 m/s. Results obtained with Micro-SWIFT-M are very similar to Mercure CFD with a short CPU time.

Figure 1 displays the wind field computed by MicroSWIT-M at building mid-height.
Figure 2 shows the comparison between MicroSWIFT, MicroSWIFT-M, MERCURE (Buty et al, 1988) and wind tunnel measurements for two locations downwind of the building. Micro-SWIFT-M gives results very similar to MERCURE. The main improvement compared to Micro-SWIFT is the smoother transition above at building height and the speed-up above.

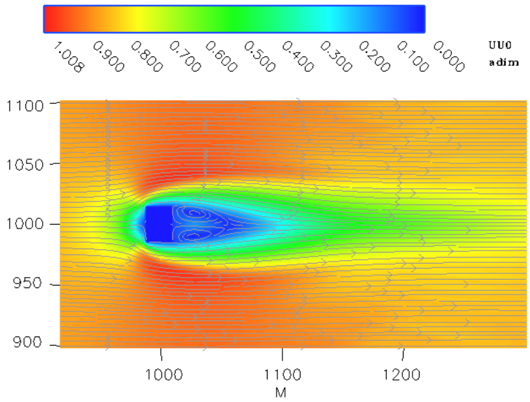

Figure 1: top view of wind speed and streamlines computed by Micro-SWIFT-M at building mid height

The CPU time on this case with a mesh of 0.5 million nodes (190×101×27 point with a 2 m horizontal resolution) is 14 min on a single Intel Xeon 5660 2.8Ghz processor.

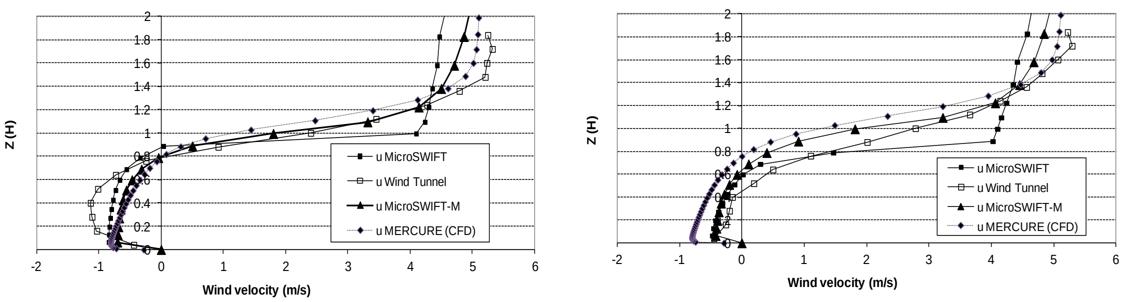

Figure 2. Rectangular building – wind speed vertical profiles at downwind distance 1.08H (left) and 1.56H (right) – Measurements, Micro-SWIFT, Micro-SWIFT-M and MERCURE

Michelstadt test case offers a more challenging academic test case. Despite a good agreement on concentration comparisons between measurements and models involved in the COST action, computed flow fields are more difficult to match with experimental data. Indeed, and due to a rather complex street geometry, wind directions in some streets are difficult to predict.
Figure 3 shows the wind field computed by Micro-SWIFT-M on a horizontal slice 6m height. Heights of buildings range from 15m to 24 m. Micro-SWIFT-M gives lower wind speed in the urban canopy. On this multi-buildings case, we observe that Micro-SWIFT-M is able to compute the cumulative effect the whole buildings where Micro-SWIFT, by construction, adds only the effect of each building and its close neighbours. Figure 4 shows the comparison at one of the vertical profiles where measurements are available. This profile is located in a canyon street that is orthogonal to the wind direction. The speed profile shows that MicroSWIFT-M slightly underestimates speed between 10m and 30m high, leading to a small overestimation above 30m. The direction profile shows that MicroSWIFT-M gives significant improvement with a better estimation of the wind direction.

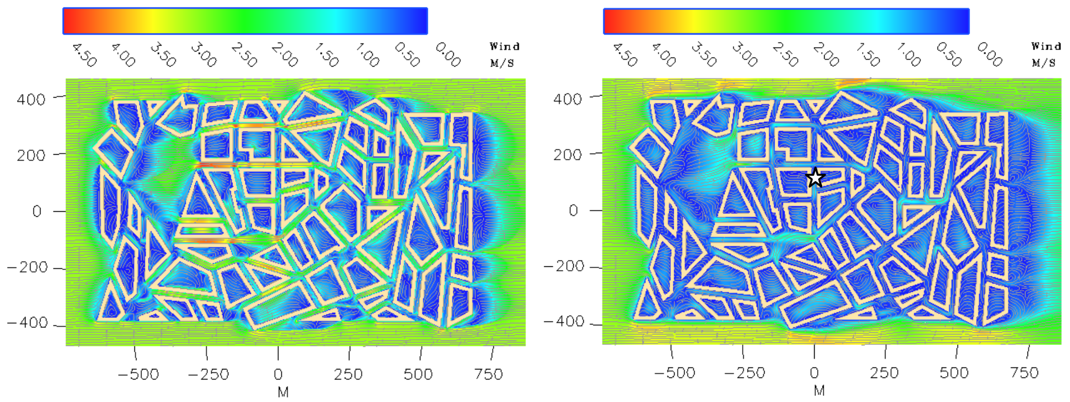

Figure 3. Michelstadt wind tunnel experiment – Wind speed (m/s) and streamlines at z=6m – Micro-SWIFT (left) and Micro-SWIFT-M (right). Star defines location for vertical comparison point

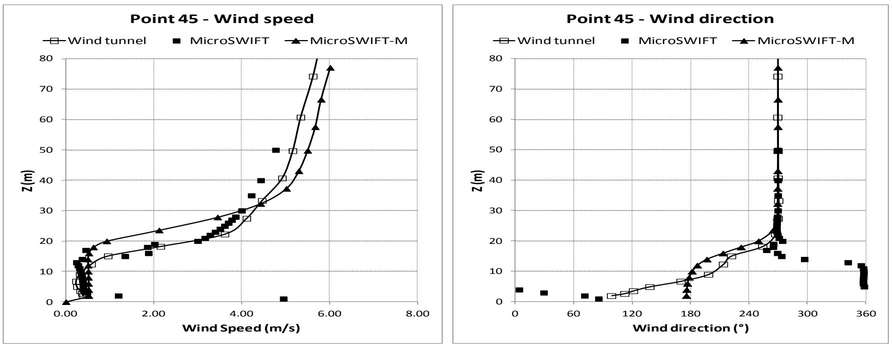

Figure 4. Michelstadt wind tunnel experiment – wind speed (left) and direction (right) vertical profiles at profile #45location (white star on Figure 3)– Measurements, Micro-SWIFT, Micro-SWIFT-M

The computation domain uses a larger mesh of 4.2 million nodes (533×309×26 points with 3 m horizontal resolution). CPU time is 1 min for Micro-SWIFT. Micro-SWIFT-M needs 58 min on a single Intel Xeon 5660 2.8 Ghz processor. Code Saturne computations have also been performed on a 6.6 million nodes mesh: CPU time is 2h40 using more than 200 Intel Xeon 5570 2.93Ghz processors (Napoly, 2013).

Paris area results: Infiltration in Gare du Nord

Gare du Nord is one of Paris railway stations. Building geometry is hollow with fine details (Nibart et al, 2011).

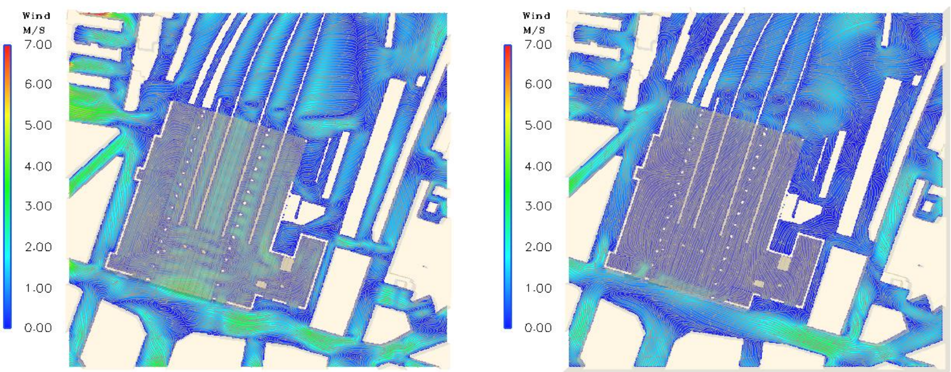

Figure 5. Gare du Nord railway station – Wind speed and streamlines at 5 m above ground –Micro-SWIFT-M (left) and Code_Saturne (right) with same mesh but different boundaries conditions

Figure 5 shows the wind field computed by MicroSWIFT-M and Code_Saturne (Archambeau et al, 2004) using an identical mesh. It should be noted that the boundaries conditions are slightly different for the two models. Code_Saturne is driven by 3D results from Micro-SWIFT on a larger domain (nesting approach) whereas MicroSWIFT-M is driven by 3D results from Micro-SWIFT on the same domain (no nest). In near future, same boundaries conditions will be used to allow the comparison. In the south on the domain, where the inlet boundaries conditions are not too different, the two models give similar flow patterns.

The computation domain is discretized with a mesh of 6.4 million nodes (385×385×43 grid points with 1 m horizontal resolution): CPU time is **1h40 on a single** Intel Xeon 5660 2.8 Ghz processor **for Micro-SWIFT-M, compared to 55min with 416 cores** Intel Xeon 5570 2.93Ghz processors **for Code_Saturne**.

CONCLUSION

Momentum conservation has been added in Micro-SWIFT. It uses simplified turbulence modelization and artificial compressibility scheme to compute steady state wind flow solution. This capability can be used at the finer scale of a downscaling computation over a large city like Paris, around specific buildings of interest to compute infiltration of dangerous contaminants. Results displayed are very promising. Quality of wind field tends to be very similar to more general CFD codes, with very short computational time. If Micro-SWIFT-M is already parallelized regarding time frames calculation, spatial domain decomposition is expected to reduce strongly the computational delay for single time frame calculations.

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