ERF: Inflow Turbulence Generation

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Theory

The box perturbation method (BPM) perturbs the temperature field (ρθ) in a volume (box) format. Each box computes a perturbation update time (Eq. 1) and amplitude (Eq. 2), then independently update at its respective update interval during runtime. A single perturbation amplitude is seen by the computational cells that falls within this box (demonstrated in figure 1 and figure 2a in dotted lines). Pseudo-random perturbations (ie. white noise) is applied over the range [-ϕ, +ϕ] then introduced to the ρθ field via source term. As temperature is transported and through the action of the subgrid-scale (SGS) filter for eddy viscosity, white noise temperature perturbations become colored noise in the velocity field. A net-zero energy enforcement is applied over the perturbation boxes to ensures the synthetic method does not introduce excess energy into the system at each iteration.

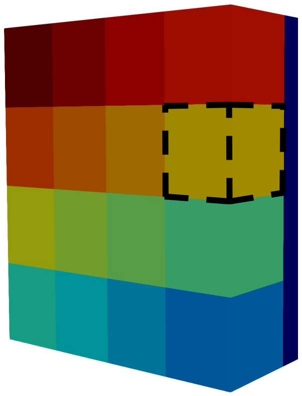

Figure 1. Box perturbation initialization with artificial fill

$$\frac{t_P \langle U(z) \rangle_{PB}}{D_{PB}} = 1 \quad (1)$$

$$Ri_{PB} = \frac{g\beta\Delta\overline{\phi}H_{PB}}{\langle U(z) \rangle_{PB}^{2}} \quad (2)$$

$$\Phi_{PB} \propto \frac{\Delta\overline{\phi}}{t_p} \quad (3)$$

$$[-\Phi_{PB}, +\Phi_{PB}]$$

White noise distribution

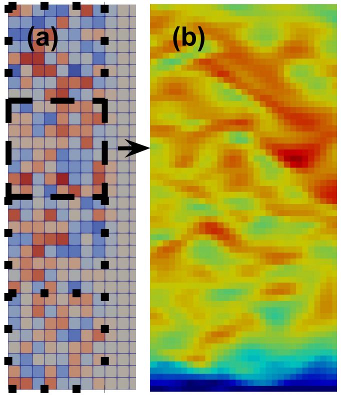

Figure 2. (a) Pseudo-random perturbation via source term. (b) Downstream flow developing into turbulence

Rule of Thumb

The general guideline is to set the perturbation box to the following,

- $H_{PB} = 0.125 L_z$
- $L_{PB} = 2 H_{PB}$
- $W_{PB} = L_{PB} \tan\left(\theta_{u,v}\right)$
- Number of layers should range from 3-5
- Number of offset from boundary is up to the user
- The Richardson value to start with is 0.042
- Temperature infinity should be set to the background temperature state.

Note that the current implementation only accepts integer values, and these recommendations are based on the physical domain size, not mesh values. Therefore, users should consider both domain size and mesh resolution when determining the dimensions of a single box.

Method Setup

To setup a perturbation zone, the user must provide ERF a variation of the following in the input file,

1. `erf.perturbation_type = “source” or “direct”`
2. `erf.perturbation_direction = 1 1 0 1 1 0 (Depending on flow direction)`
3. `erf.perturbation_layers = 3                (Recommended)`
4. `erf.perturbation_offset = 3-5              (Recommended)`
5. `erf.perturbation_box_dims = 8 8 4          (Reference “Rule of Thumb Page”)`
6. `erf.perturbation_nondimensional = 0.1      (Bulk Richardson Number)`
7. `erf.perturbation_T_infinity = 300.0        (Background temperature)`

Runtime Outputs

During runtime, a file named “BoxPerturbationOutput.0” is generated, containing initialization data for the perturbation boxes and per-box information based on the user-defined frequency. The output frequency is controlled by setting `erf.pert_interval = n`, where `n` specifies the number of timesteps between each perturbation box information output. Performing `tail -f` on the file during runtime updates the user in the terminal with the calculated perturbation values for each box. Example outputs are shown below.

```
Setting perturbation region in: West face
BoxList: (BoxList 1 (C,C,C)
1 : ((3,0,0) (26,15,63) (0,0,0))
)

perturbation_box_dims: 8 8 4
perturbation_direction: 1 0 0

perturbation_layers: 3
perturbation_offset: 3

perturbation_nondimensional: 0.1
perturbation_T_infinity: 300
perturbation_T_intensity: 0
Reference length per box = 1.76777
```

```
#################### PB output at time = 165.28 ####################
 Using type: 0
 Net: -1.38778e-17 Adjust : -1.4456e-19
[0] pb_Umag=0.391245 | pb_interval=4.93153 (2.6996) | pb_amp=0.151875
[1] pb_Umag=0.342591 | pb_interval=5.5522 (4.4586) | pb_amp=0.103433
[2] pb_Umag=0.314447 | pb_interval=6.14589 (1.536) | pb_amp=0.0787194
[3] pb_Umag=0.391817 | pb_interval=4.65476 (2.9842) | pb_amp=0.161377
[4] pb_Umag=0.342782 | pb_interval=5.3001 (4.594) | pb_amp=0.108473
[5] pb_Umag=0.312352 | pb_interval=5.59222 (5.5416) | pb_amp=0.0853645
[6] pb_Umag=0.565734 | pb_interval=3.17607 (2.0704) | pb_amp=0.493068
[7] pb_Umag=0.581354 | pb_interval=2.86661 (0.682) | pb_amp=0.576881
[8] pb_Umag=0.584647 | pb_interval=3.20425 (0.5916) | pb_amp=0.521955
[9] pb_Umag=0.566185 | pb_interval=2.84133 (2.168) | pb_amp=0.552036
[10] pb_Umag=0.582367 | pb_interval=3.07203 (0.3682) | pb_amp=0.540181
[11] pb_Umag=0.583935 | pb_interval=3.00283 (0.9052) | pb_amp=0.555611
[12] pb_Umag=0.609314 | pb_interval=2.63435 (0.9396) | pb_amp=0.689575
```

Cautionary Warnings

Before setting up the perturbation region, users should run a short simulation to ensure the base state is stable. Once verified, add the targeted perturbation tags to initialize the buoyant region.

During runtime, the simulation may crash due to an “Erroneous Arithmetic Operation”. This usually occurs when the perturbation introduced into the potential temperature field is too large. To prevent this, several changes can be taken to reduce the perturbation amplitude:

- Increasing the perturbation box size
- Reduce the Richardson number

Function Locations

The functionality of the turbulent inflow generation method primarily exists in `Source/DataStructs/TurbPertStruct.H`, with function calls existing in the following files,

- `Source/ERF.H`
- `Source/ERF.cpp`
- `Source/Initialization/ERF_init_TurbPert.cpp`
- `Source/SourceTerms/ERF_make_sources.cpp`
- `Source/TimeIntegration/ERF_Advance.cpp`

Debugging Strategies

1. Check “BoxPerturbationOutput.0” for correct number of perturbation box output
2. Visually check the initialization of the box perturbation region in Paraivew/Visit
   a. The buoyant region is initialized a t=0(s), and can bee seen in the $\rho\theta$ field.
3. Switching on `#define INDEX_PERTURB` inside of `Source/DataStructs/TurbPertStruct.H`, and recompile to see how the boxes are being created.
   a. This should only be used as a debugging step

References

- Munters, Wim, Charles Meneveau, and Johan Meyers. "Shifted periodic boundary conditions for simulations of wall-bounded turbulent flows." *Physics of Fluids* 28.2 (2016).
- DeLeon, Rey, Clancy Umphrey, and Inanc Senocak. "Turbulent inflow generation through buoyancy perturbations with colored noise." *AIAA Journal* 57.2 (2019): 532-542.
- Ma, Ting-Hsuan, and Inanc Senocak. "Lateral Boundary Conditions for Complex Terrain Wind Simulations with Oblique Inflow Direction." *Boundary-Layer Meteorology* 187.3 (2023): 567-590.