A Comparative Study of a Spatially Evolving Self-Propelled Wake and a Patch of Turbulence

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Introduction

A body moving under its own power leaves behind a special kind of wake, referred to as a self-propelled wake. The typical characteristic of such a wake is the presence of thrust and drag in the velocity profile. There are two ways of modeling the self-propelled wake computationally: temporally evolving or spatially evolving. A temporal simulation assumes a frame that moves with the background flow velocity in the downstream direction whereas the spatial simulation is done in the inertial frame of reference.

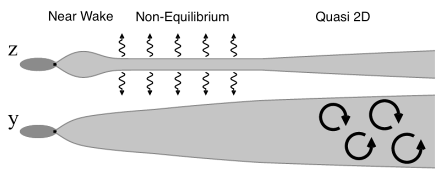
Research Questions

❑ Is the commonly used temporal approximation correct for a spatially evolving self-propelled wake given consistent initial and inflow conditions?

❑ What is the relative role of mean velocity and turbulence in the dynamics of a turbulent wake?

Background

Spatial evolution of a stratified wake showing the three regimes



Wake evolution in the vertical, *z* and horizontal, *y* directions. Curvy arrows show the location where the internal waves are significant and the pancake eddies are shown in the late wake.

Governing Equations

3D incompressible, unsteady non-dimensional Navier-Stokes equations, Boussinesq approximation

Mass: $\frac{\partial u_k}{\partial x_k} = 0$ Momentum: $\frac{\partial u_i}{\partial t} + \frac{\partial (u_k u_i)}{\partial u_k} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 u_i}{\partial x_k \partial x_k} - \frac{1}{Fr^2}\rho' \delta_{i3}$

Density: $\frac{\partial \rho}{\partial t} + \frac{\partial (u_k \rho)}{\partial u_k} = \frac{1}{Re\,Pr}\frac{\partial^2 \rho}{\partial x_k \partial x_k}$ $Re = \frac{UD}{\nu}$, $Fr = \frac{U}{ND}$, $Pr = \frac{\nu}{\kappa}$

Simulation Details, Initial and Boundary Conditions

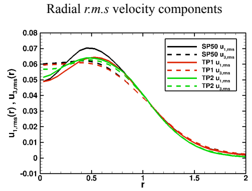
❑ DNS on staggered grid arrangement, Explicit RKW3 for time advancement, 2nd order central difference scheme for spatial derivatives.

❑ Multigrid pressure solver with RB Gauss-Seidel with SOR as smoother, 3D domain decomposition, parallelization with MPICH-II.

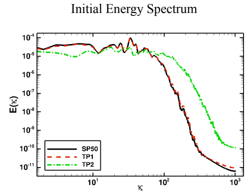
❑ ICs for the self-propelled wake (SP50) match with Brucker & Sarkar *JFM* 2010.

❑ ICs for turbulent patch (TP1 & TP2) are generated by solving the unstratified NS equations for a few time units to develop similar or higher energy in small scales.

Radial *r.m.s* velocity components



Initial Energy Spectrum

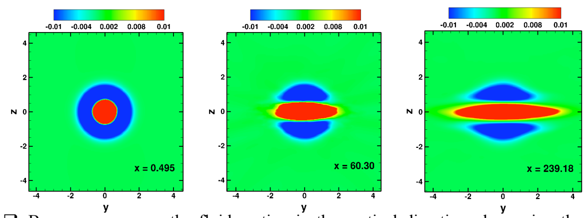


❑ Auxiliary simulations with periodic BCs in *x* are used for generating the inlet BCs for the spatially evolving simulations.

❑ Extrapolation BCs at outflow and far field BCs in *y* and *z* directions for both auxiliary and spatial simulations.

❑ Re=15000, Pr=1, Fr=3; 400 million grid points, 20000 CPU hours.

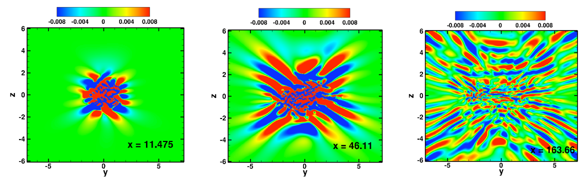
Evolution of the Mean Velocity Profile



❑ Buoyancy opposes the fluid motion in the vertical direction, decreasing the kinetic energy to support the density fluctuations.

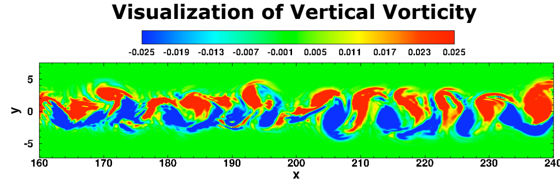
❑ Suppression and collapse of the wake in the vertical direction and expansion in the horizontal direction.

Visualization of Internal Gravity Waves



❑ Internal gravity waves propagate energy to the background due to the turbulence in the wake.

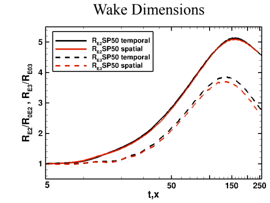
Visualization of Vertical Vorticity



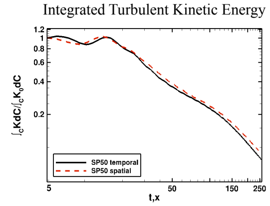
❑ Pairing of small vortices lead to the formation of large coherent vortical structures in late wake .

Temporal and Spatial Evolution Match Well

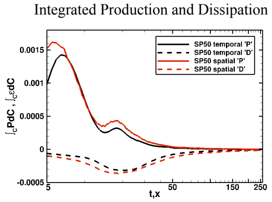
Wake Dimensions



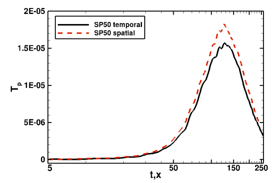
Integrated Turbulent Kinetic Energy



Integrated Production and Dissipation



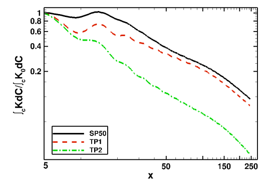
Waveflux



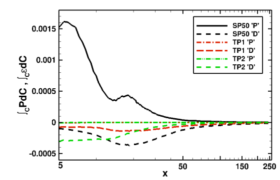
Self-Propelled Wake vs. Turbulent Patch

(SP50) (TP1 &TP2)

Integrated Turbulent Kinetic Energy



Integrated Production and Dissipation



$$\frac{DK}{Dt} = \text{Shear Production} + \text{Buoyancy Flux} - \text{Dissipation} - \text{Turbulent Transport}$$

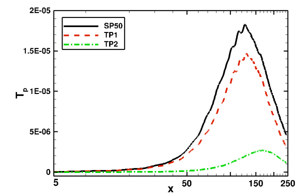
❑ Initial differences in the decay of turbulent kinetic energy (K) are due to high production in SP50 and negligible production in TP1 and TP2 (no mean).

❑ Production in SP50 extracts energy from the mean shear and transfers it to the fluctuations.

❑ In response to the initial increase in K for SP50, the dissipation also increases and the decay rate becomes similar to TP1 for $x > 65$.

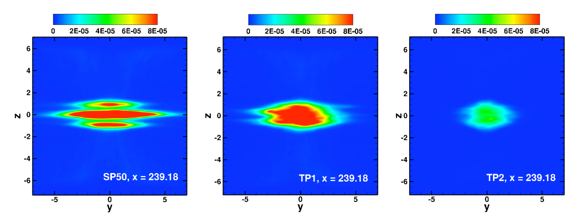
❑ Higher energy in the small scales lead to larger initial dissipation for TP2.

Waveflux



❑ Energy propagated to the background in the form of waves is higher in SP50 as compared to TP1 and TP2 due to the higher turbulent kinetic energy at early stages.

Turbulent Kinetic Energy



❑ The P_{13} component of production is responsible for the presence of lobes in the vertical direction for SP50 and is a distinctive feature from TP1 and TP2

Conclusions

❑ The temporal assumption with consistent initial and inflow conditions is valid for a spatially evolving self-propelled wake.

❑ Large values of mean kinetic energy influence the near wake dynamics significantly but in the late wake the evolution is similar to a patch of turbulence with the same initial energy spectrum.

❑ Higher turbulence in the small scales result in faster decay of the turbulent kinetic energy of TP2 as compared to SP50 and TP1.