Simulation of a self-propelled wake with excess momentum in a stratified fluid

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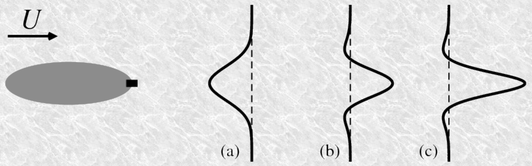
Motivation

Wake studies usually consider steady-state towed or self-propelled cases despite steady motion being an unrealistic assumption due to unsteady upstream conditions, slight imbalances in thrust and drag, and the presence of maneuvers. It is generally thought that a small amount of injected momentum during acceleration/deceleration qualitatively changes wake behavior from a self-propelled wake to a momentum dominated wake, however this has not been shown numerically or experimentally.

Principal motivation: How does a small amount of excess momentum impact a self-propelled wake?

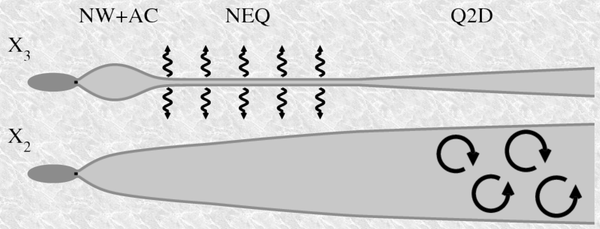
Background

Wake velocity profiles



Velocity profile behind a moving body. (a) Towed wake (b) Self-propelled wake with zero net momentum. (c) Propelled wake with excess momentum.

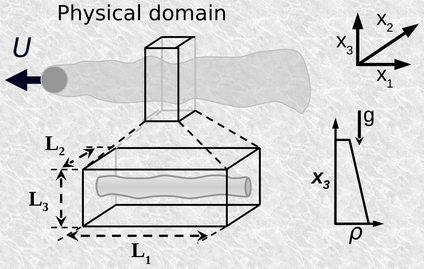
Spatial evolution of a stratified wake



Wake evolution in the vertical, x_3, and horizontal, x_2, directions. Curvy arrows show the time when internal waves are significant and pancake eddies are shown in the late wake.

Formulation

Physical domain



Computational domain

Figure from K. Brucker, Ph.D. Thesis, UCSD, 2009

Simulation details

- Direct numerical simulation
- Temporal approximation
- Fully explicit staggered-grid
- 2nd order in space
- 3rd order in time (RK3)
- Multigrid pressure solver
- 3D domain decomposition
- Parallelization with MPICH-II

Computational cost

Re=10,000, Fr=3,20 cases	415 million grid points, 1,600 CPU hours
Re=25,000, Fr=3 cases	1.29 billion grid points, 5,500 CPU hours

Governing equations

3D incompressible, unsteady Navier-Stokes equations, Boussinesq approx.

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

Density $$\frac{\partial \rho}{\partial t} + \frac{\partial (u_k \rho)}{\partial x_k} = \frac{1}{RePr}\frac{\partial^2 \rho}{\partial x_k \partial x_k}$$ Mass $$\frac{\partial u_k}{\partial x_k} = 0$$

$$Re = \frac{UD}{\nu}, \qquad Fr = \frac{U}{ND}, \qquad Pr = \frac{\nu}{\kappa}$$

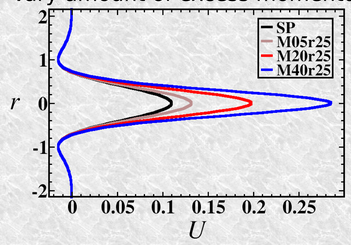
Adding excess momentum

Model maneuvers as an impulsive addition of thrust

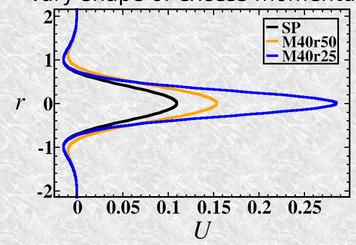
Excess momentum applied as a Gaussian profile

- Vary the amount of excess momentum: 5, 20, 40 % momentum
- Vary the shape of excess momentum: narrow (r25) and wide (r50) jet

Vary amount of excess momentum



Vary shape of excess momentum



Increasing the amount and/or decreasing the radial extent of excess momentum increases the defect velocity, mean kinetic energy, and shear in the velocity profile.

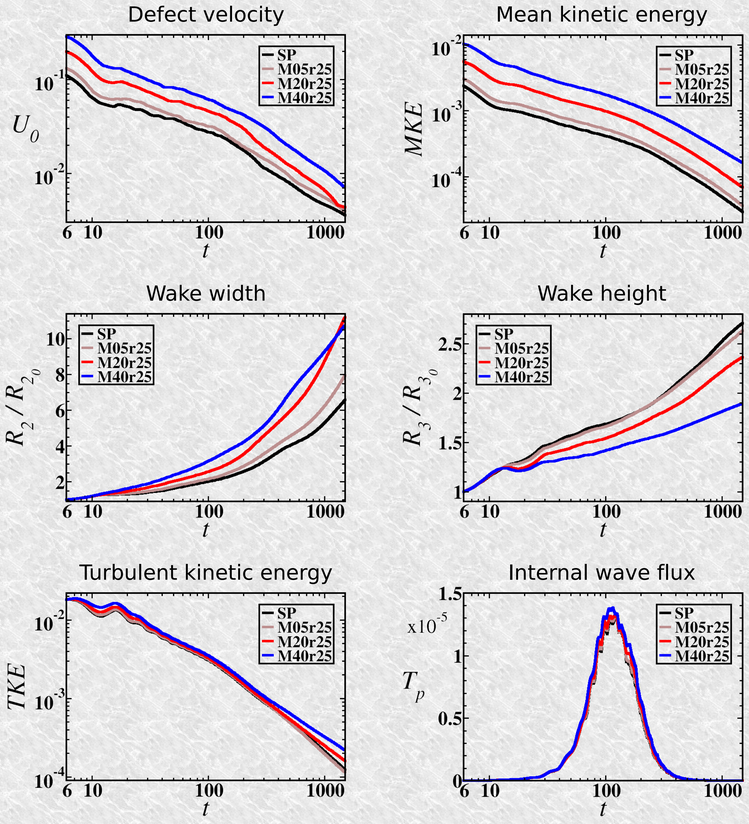
Adjustment procedure couples turbulent fluctuations to mean profile

Simulations performed with Re=10,000, Pr=1, and Fr=3

Narrow jet, 40% momentum case reconsidered at

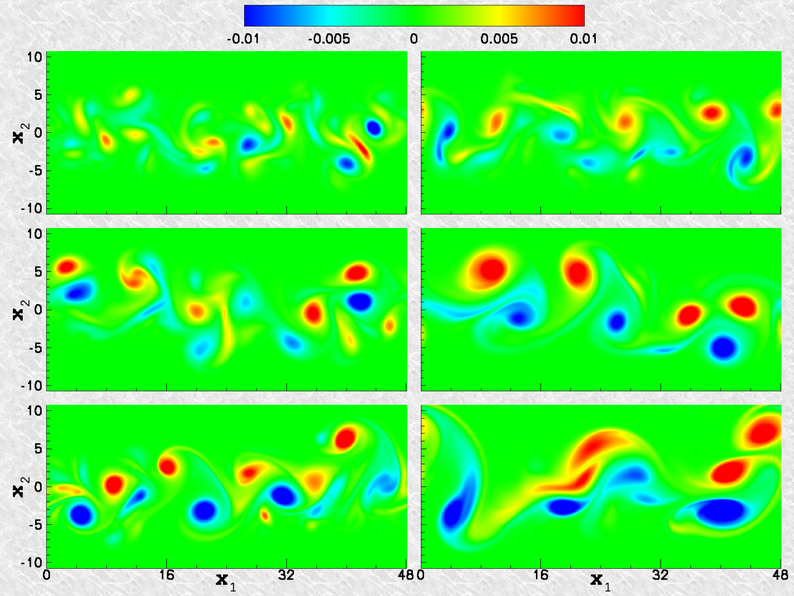
- Re=10,000, Fr=20 to study effect of Froude number
- Re=25,000, Fr=3 to study effect of Reynolds number

Wake evolution



Excellent qualitative agreement occurs for turbulent and mean flow statistics

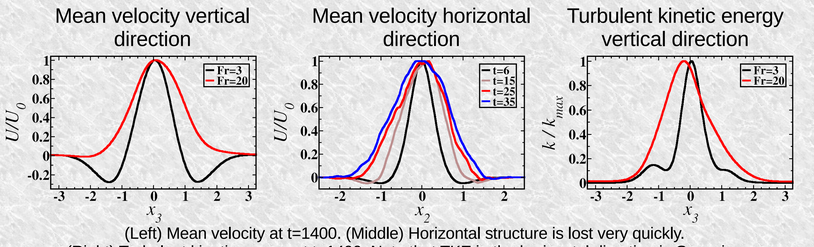
Late wake eddies



Late wake vorticity: ω_3 (x_3=0) at t=1400.

(Left column) Self-propelled. (Right column) 40% excess momentum. (Top) Re=10,000, Fr=20. (Middle) Re=10,000, Fr=3. (Bottom) Re=25,000, Fr=3.

Wake structure



(Left) Mean velocity at t=1400. (Middle) Horizontal structure is lost very quickly.
(Right) Turbulent kinetic energy at t=1400. Note that TKE in the horizontal direction is Gaussian.

Conclusions

Principal conclusion: A self-propelled wake with a small amount of excess momentum behaves qualitatively like a self-propelled wake.

Adding a small amount of excess momentum (see [1] for details)

- Increases defect velocity, mean kinetic energy, shear in velocity gradient
- Increased shear → higher production → higher turbulent dissipation
- Buoyancy decouples thrust and drag lobes in the vertical direction
- Excess momentum trapped near vertical center
- Wake expands in horizontal and large scale structures formed

Results are *not* sensitive to Reynolds number

Some changes with increasing Froude number

[1] M.B. de Stadler and S. Sarkar, Simulation of a self-propelled wake with small excess momentum in a stratified fluid. *Journal of Fluid Mechanics,* 2011 (under review).

Future work

Spatially evolving simulations with a body in the domain.

Acknowledgments

Matthew de Stadler received support from the Department of Defense (DOD) through the National Defense Science & Engineering Graduate Fellowship (NDSEG) Program, a Jacobs School Fellowship (UCSD), and an Achievement Rewards for College Scientists Scholarship. Partial support was provided by ONR grant N000140710133.