Preferential Alignment and Heterogeneous Distribution of Non-spherical Swimmers Near Lagrangian Coherent Structures

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Abstract

We report the interaction between non-spherical swimmers and a long-standing flow structure, Lagrangian coherent structures (LCSs), in a weakly turbulent two-dimensional flow. Using a hybrid experimental-numerical model, we show that rod-like swimmers have a much stronger and more robust preferential alignment with attracting LCSs than with repelling LCSs. Tracing the swimmers' Lagrangian trajectories, we reveal that the preferential alignment is the consequence of the competition between the intrinsic mobility of the swimmers and the reorientation ability of the strain rate near the attracting LCSs. The strong preferential alignment with attracting LCSs further leads to a strong clustering near the attracting LCSs. Moreover, we show the self-similarity of this clustering, which reduces the intricate interaction to only one control parameter. Our results generically elucidate the interaction between active and non-spherical swimmers with LCSs and, thus, can be widely applied to many natural and engineered fluids including ocean flow.

Preferential Alignment and Heterogeneous Distribution of Non-spherical Swimmers Near Lagrangian Coherent Structures (LCS)

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Introduction

[Overview]

We report the interaction between **active non-spherical swimmers** and a long-standing flow structure, **Lagrangian coherent structures (LCSs),** in a weakly turbulent two-dimensional flow.

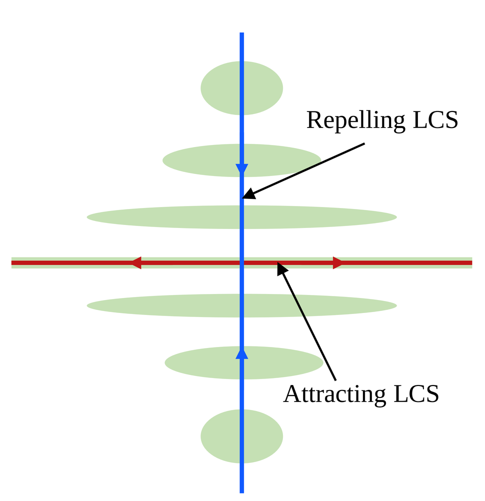
[Method]

Using a **hybrid experimental–numerical model**, we feed virtual swimmers to an experimentally measured flow field using particle tracking velocimetry (PTV). Swimmers are modeled as inertia-less, noninteracting, point-like prolate ellipsoids. The motion of swimmers are governed by **Jeffery's equation**. *(In general, Jeffery's equation states that swimmers with a higher aspect ratio have a stronger reorientation response to the local strain rate field, and the swimmers will also be reoriented according to the local vorticity field.)*

[Conclusions] We show that:

- Rod-like swimmers have a much **stronger** preferential alignment with attracting LCSs than with repelling LCSs (refer to the full paper for details about this finding)..
- The **preferential alignment** results from the competition between the intrinsic mobility of the swimmers and the reorientation ability of the strain rate near the attracting LCSs.
- The strong preferential alignment with attracting LCSs further leads to a strong **accumulation** near the attracting LCSs.
- We show the **self-similarity** of this accumulation, which reduces the intricate interaction to only one control parameter.

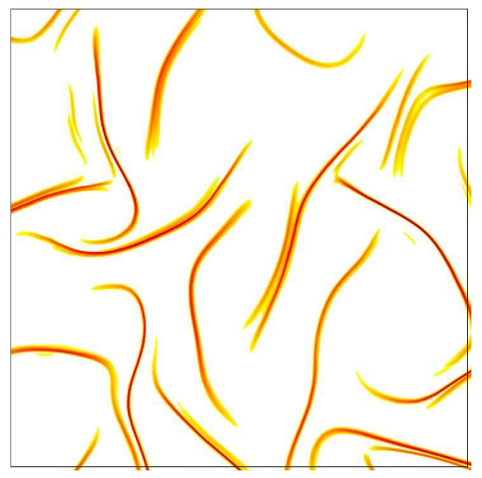
What is LCS ?



LCSs are robust features of Lagrangian fluid motion that describe the most repelling, attracting, and shearing material surfaces that form the skeletons of Lagrangian particle dynamics.

Consider the diagram above in which the two green blobs at top and bottom represent two fluid particles. As these two fluid particles move toward the center, they are stretched in horizontal direction while compressed in vertical direction. In other words, they are repelled by the blue line while attracted to the red line. These two regions (red line and blue line) that experience the strongest repelling and attracting forces are called repelling LCS and attracting LCS.

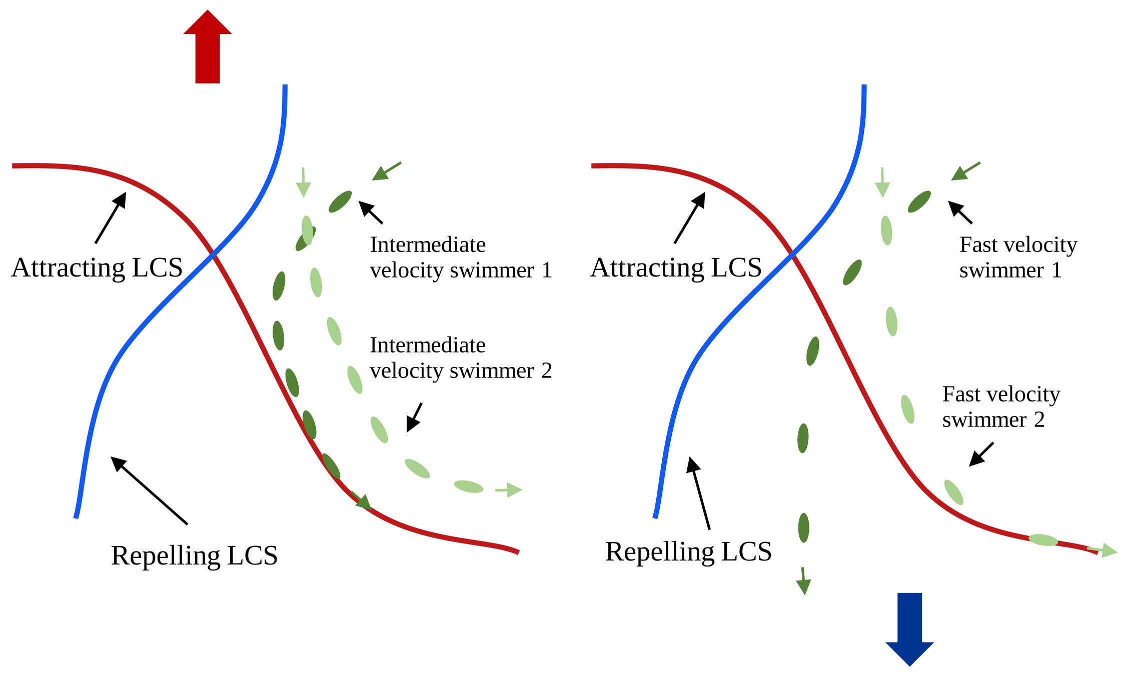
This figure shows the attracting LCSs in a measured flow field calculated by the most used method - Finite Time Lyapunov Exponent (FTLE) method.



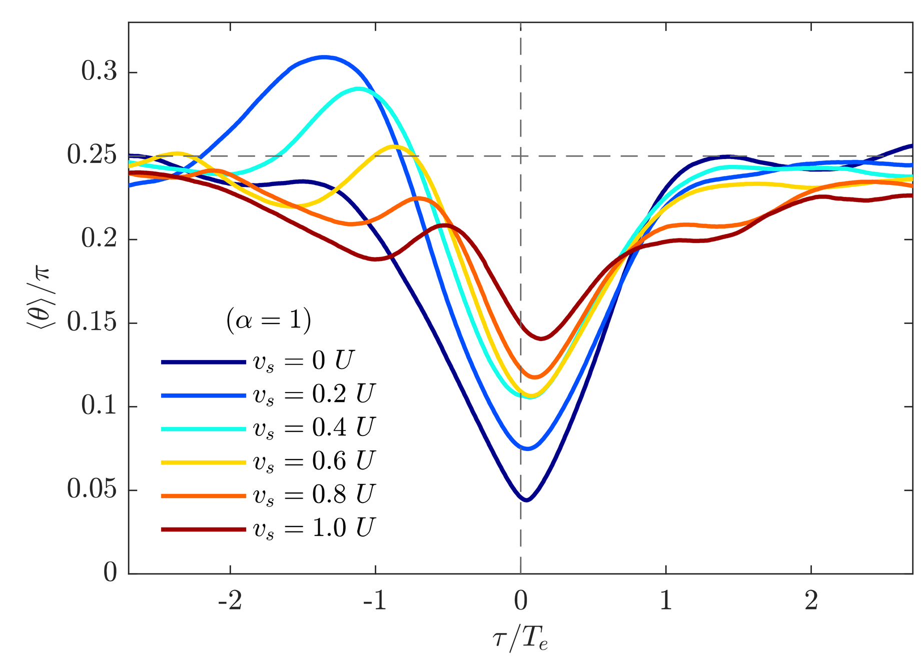
Key Result 1

- Elongated swimmers preferentially align with LCSs.
- Attracting LCSs preferentially sample swimmers with **intermediate intrinsic velocity** (relative to the flow field) that was **initially more perpendicular** to the attracting LCSs.
- Attracting LCSs preferentially sample swimmers with **fast intrinsic velocity** that was **initially more tangential** to the attracting LCSs.

Discussion: in this case, the reorientation ability of the **strain rate** near the attracting LCS **dominates** the swimmer's mobility, and a swimmer must be more perpendicular to the attracting LCS to eventually reach and align with it. Otherwise, a swimmer will be reoriented to be parallel to the attracting LCS before reaching it due to the strong reorientation ability of the strain rate and will never reach the attracting LCS.



Discussion: in this case, the swimmer's mobility dominates the reorientation ability of the strain rate near the attracting LCS, and a swimmer must be more parallel to the attracting LCS to eventually align with it. Otherwise, the swimmer will penetrate the attracting LCS due to the strong mobility.

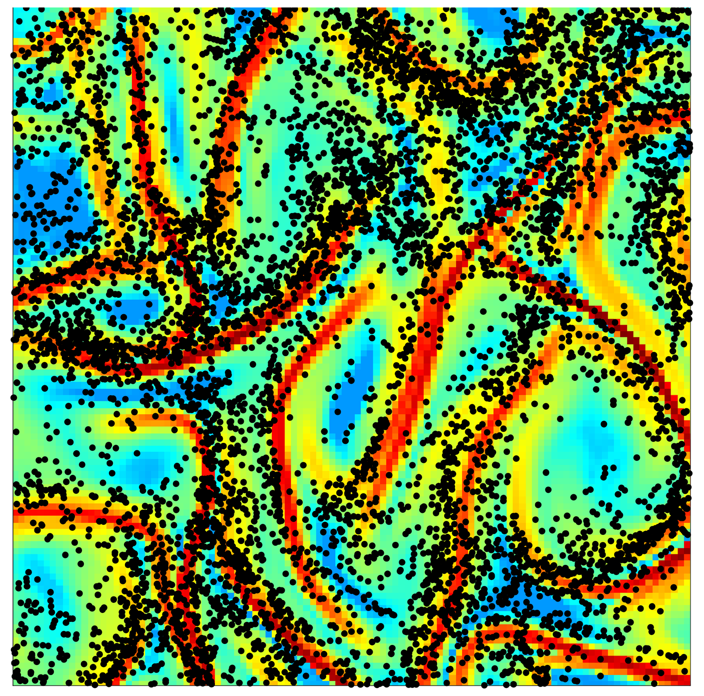


This figure quantitatively supports the result above. It shows the Lagrangian history of the alignment between swimmers and attracting LCSs. It can be noticed that swimmers with intermediate swimming velocity has a mean angle greater than $\pi/4$ before reaching the attracting LCSs at $\tau = 0$ while fast swimmer has a mean angle smaller than $\pi/4$ before reaching the attracting LCSs.

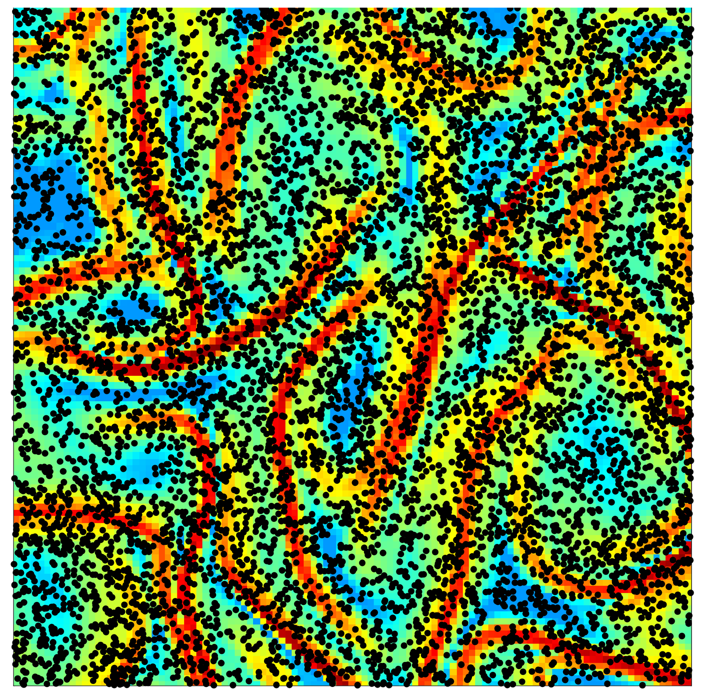
*** Random angle distribution gives a mean angle of $\pi/4$*

Key Result 2

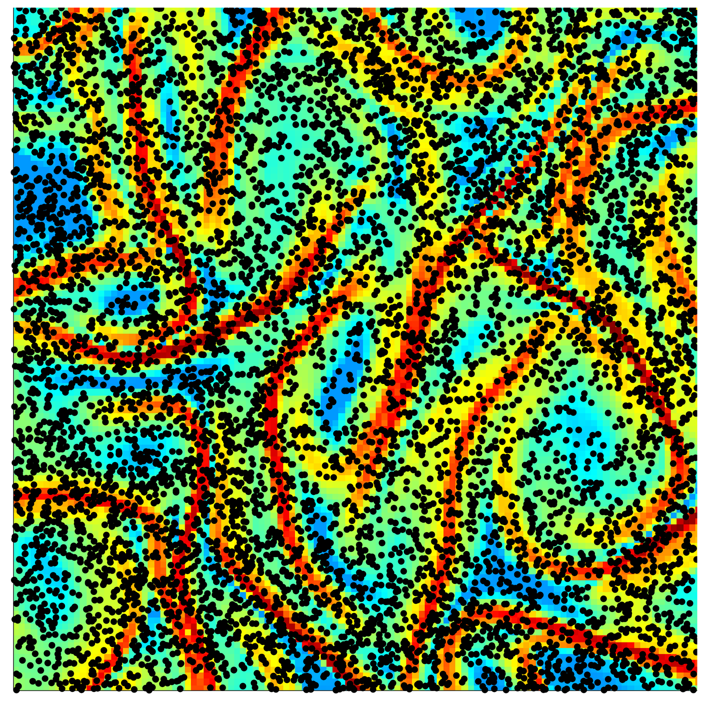
Swimmers with **intermediate intrinsic velocity** and **elongated shape** preferentially accumulate near LCSs, which results in a **heterogeneous distribution**.



$\boldsymbol{V_s = 0.5\,U, \alpha = 1}$



$\boldsymbol{V_s = 0.5\,U, \alpha = 0.1}$



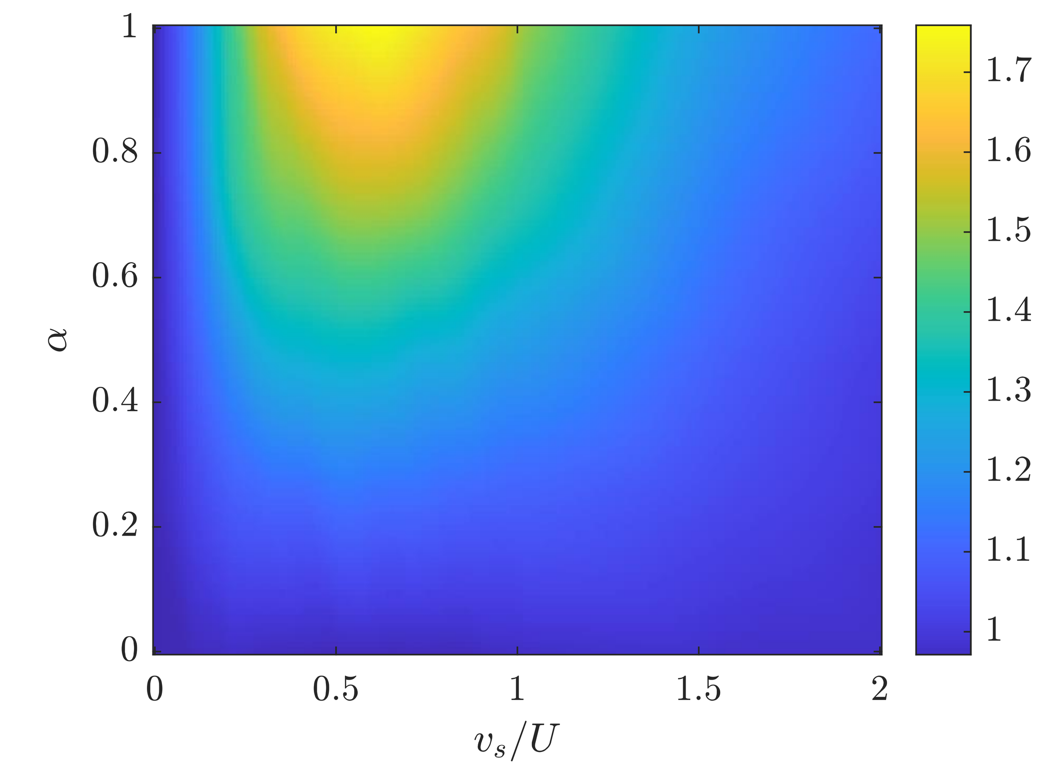
$\boldsymbol{V_s = 3\,U, \alpha = 1}$

V_s : intrinsic swimming velocity of swimmers

U : root mean square velocity of the flow field

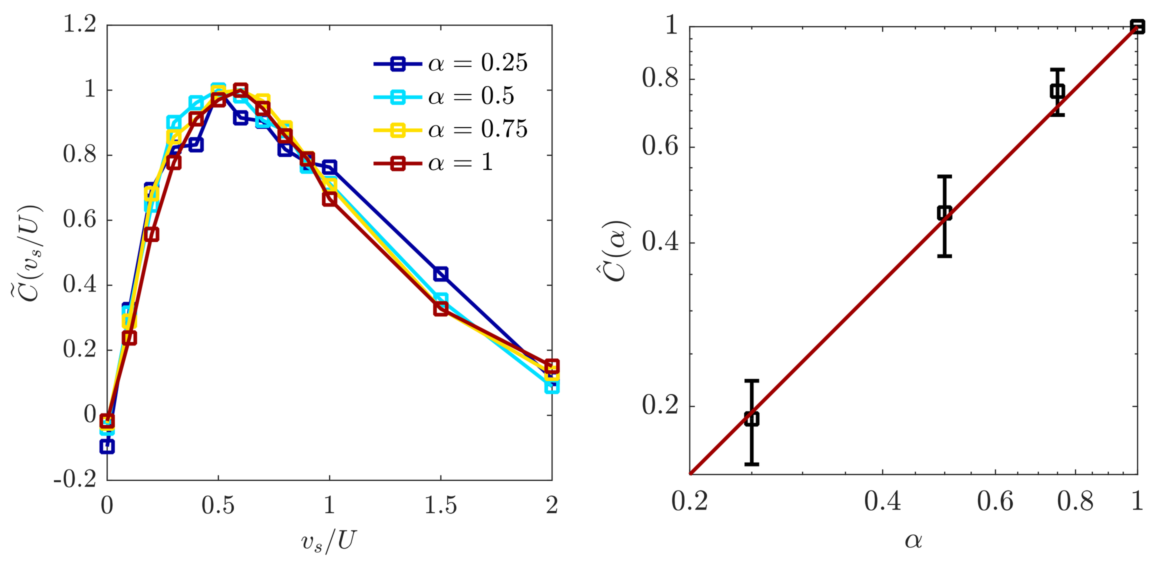
α : shape factor, $\alpha = 1$ means rod-like, $\alpha = 0$ means spherical

*** Red color regions are attracting LCSs*



The normalized concentration C (by the concentration assuming uniform distribution) of swimmers with α ranging from 0 to 1 and V_s ranging from 0 to 2U near attracting LCSs. It can be noticed that elongated swimmers with intermediate intrinsic swimming velocity preferentially accumulate near attracting LCSs.

For slow swimmers, the accumulation effect is limited by the swimmer's intrinsic mobility. For fast swimmers, however, the accumulation effect is limited by the limited reorientation ability of the strain rate near the attracting LCSs. Spherical swimmers show no noticeable accumulation effect since they do not respond to the strain rate.



With this two figure, we show the self-similarity of the heterogeneous distribution. With appropriate scaling, the concentration profile with different α and different V_s can collapse into a single curve.

Scan here for the full paper

X. Si and L. Fang, " Preferential alignment and heterogeneous distribution of active non-spherical swimmers near Lagrangian coherent structures," Phys. Fluids 33, 073303 (2021)