IDENTIFYING PARTICLE CLUSTERS IN TURBULENT FLOW

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Abstract We present a new method of identifying particle clusters in turbulent particle-laden flow. While earlier particle cluster definitions are based on a global density threshold, our method is based on localising local particle density maxima in a plane. The particle clusters are defined as connected regions where at least two of the eigenvalues of the Hessian of the particle concentration are negative. We test the method on a simple vortex array, where we observe that the heavy particles cluster in the straining regions between the vortices.

BACKGROUND

Inertial particles in a turbulent flow tend to cluster in certain regions of the flow. The tendency for particles to distribute inhomogeneously in space is known as preferential concentration [3], and the study of this phenomenon is relevant to many industrial applications.

The ability to identify particle clusters in a flow allows us to study the formation and breakup of clusters, as well as their connection with flow structures. Particle clusters can be seen as particle structures characteristic of the particle phase flow, and their topology and dynamics should reveal interesting features of the particle flow.

For the study of particle clusters, a definition is required to identify the particles that are part of clusters. While it can be stated that a particle cluster is a contiguous region of high particle concentration, no agreed-upon definition exists. Several different methods are used to characterise clustering and clusters [2], and cluster definitions are usually based on a global particle concentration threshold. Connected regions with particle concentrations higher than the threshold value are considered as clusters. The particle concentration values are obtained either by dividing the domain into a box-counting grid, or by using a Voronoï diagram. Although in both cases a global concentration threshold is set, one advantage of using a Voronoï diagram is that a threshold value presents itself naturally from the relative probability density function [1].

In homogeneous turbulence, a cluster identification method based on a global particle concentration threshold is a practical approach. However, in turbulent shear flows, strongly inhomogeneous average spatial distributions are often found, making it difficult to find local particle clusters in the low-concentration regions. In a turbulent channel flow, there is a strong tendency for particles to concentrate in the near-wall regions. A cluster identification method based on a global threshold would either find no particle clusters in the centre of the channel, or describe the entire near-wall region as one large cluster.

If a particle cluster is understood as a local, rather than a global, particle concentration peak, then the particle identification method cannot be based on a global threshold value when applied to non-homogeneous flows.

A PARTICLE CLUSTER IDENTIFICATION METHOD

A sound definition of a particle cluster should be intelligible and closely related to our understanding of a particle cluster as a contiguous region of high particle concentration. The particle concentration $\phi(x, y, z)$ is defined as the number of particles per unit volume, and we assume for now that ϕ is known as a function of the spatial coordinates (x, y, z).

We define a particle cluster as a local maximum of the particle concentration ϕ in a plane. This can be expressed using the Hessian Φ, where $\Phi_{ij} = \partial^2\phi/\partial x_i \partial x_j$. A local maximum in a plane requires two negative eigenvalues of Φ, which means the second largest eigenvalue λ_2 must be negative. We can define a particle cluster as a connected region of $\lambda_2(\Phi) < 0$. Particle clusters can then be illustrated by plotting iso-surfaces of negative λ_2.

This particle cluster definition requires knowledge of ϕ and its derivatives, while the information we have available is a set of discrete particle coordinates. In order to find and differentiate the particle concentration, it is necessary to divide the domain into a computational mesh. Both a Voronoï diagram and a standard Cartesian mesh are possible choices. Derivatives on a Voronoï diagram can be computed by treating the diagram as a finite volume mesh, and performing a surface integral over the cell. A Voronoï diagram has the advantage of providing particle-level detail; when visually inspecting the structure of particle clusters, a Cartesian grid is more convenient.

In addition to being able to identify particle clusters, it is sometimes useful to characterise the degree of clustering using a dispersion index. Many such indices exist, but few give values that are easily interpretable. When a particle cluster definition is created, a simple clustering or dispersion index can be defined as the probability of a randomly chosen particle being part of a cluster.

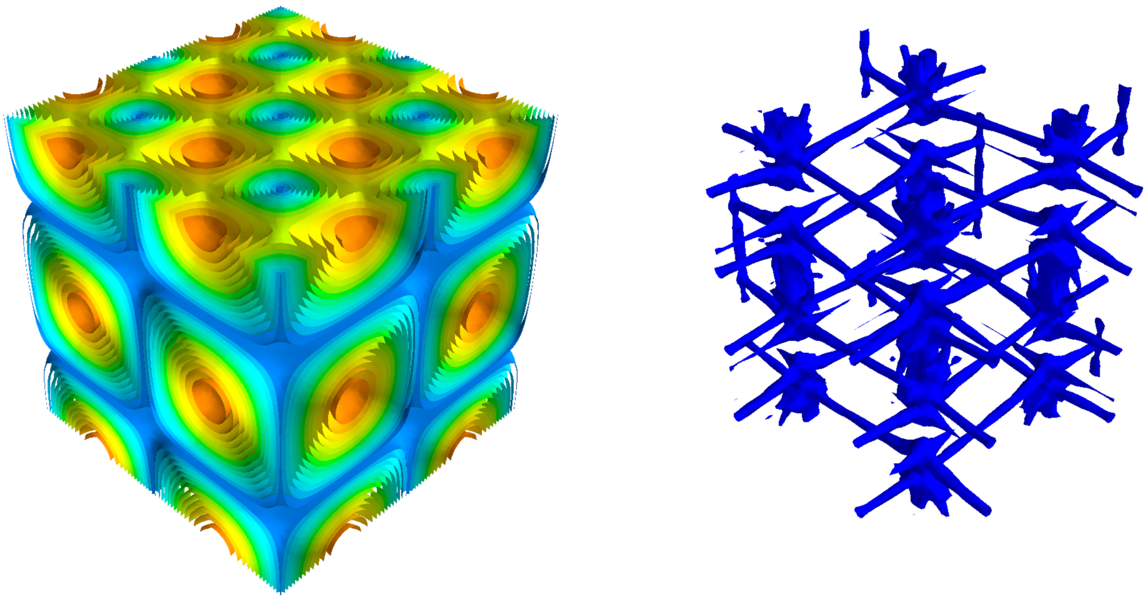

Figure 1. Isosurfaces of velocity magnitude for vortex array, $u = \cos x \sin x \cos z$, $v = -\sin x \cos y \cos z$, $w = 0$ on $(0, 2\pi) \times (0, 2\pi) \times (0, 2\pi)$, (left), and $\lambda_2 = -0.15(\lambda_2)_{\max}$ iso-surface (right). The flow is periodic with a period of 2π in each direction.

RESULTS

To illustrate how the presented method can be used to study particle clustering, we consider a test case of heavy particles in a vortex array (figure 1, left). A swarm of 20 million particles ($\mathrm{St} = 1$, $\rho_p/\rho \gg 1$) was released at random in a steady vortex array and simulated until $t = 15$. The particle distribution function ϕ was then computed on a $75 \times 75 \times 75$ equidistant Cartesian mesh, and used to find λ_2. An iso-surface of λ_2 is used in figure 1 (right) to define the surface of a particle cluster.

The particle clusters are located in the straining regions in-between the vortices in the vortex array, as expected for heavy particles. It is interesting to observe that in addition to the large cluster centres, there are smaller tube-like structures connecting the cluster centres together. These are local particle density peaks, creating a more complex structure than one might expect for such a simple flow.

A thorough analysis of the use of λ_2 iso-surfaces to identify particle clusters, is currently underway; comprehensive comparisons with other cluster identification methods will be performed. We will also apply these methods to study clustering in real turbulent flows, using data from direct numerical simulations. We believe that this can help give a better understanding of the spatial structure of particle clusters, and how they relate to flow structures.

References

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