学 位 論 文 内 容 の 要 旨
Abstract of Doctoral Dissertation

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Local-heterogeneous responses and transient dynamics in colloidal fluids
（コロイド流体における局所的な不均一応答と動態）

All living organisms are composed of basic structural, functional, and biological unit such as cell. In biology, cell movement is one of the basic components to determine the phenotype in a living body. The motility of cells is a highly dynamic phenomenon that is essential to a variety of biological processes such as the embryonic development, wound healing, immune response and the cancer metastasis. For example, in wound healing in animals, white blood cells and macrophages move to the wound site to kill the microorganisms that cause infection. In most of the case, cells reach their target by crawling and sometimes they are found to move collectively. This collective motion indeed refers the heterogeneity in space and time of cells' motility in a living organism.

Motion within a confluent epithelial cell sheet exhibits a collective migration and subcellular motion but, depending on the presence of their neighbors. At large length scales and time scales, collective migration slows as cell density rises. This behavior has an intriguing analogy to dynamic heterogeneity in a system composed of many particles as they become more crowded. To that end, this thesis mainly investigates a quasi-two-dimensional colloidal fluid to understand the heterogeneous behavior of particles in terms of the underlying dynamical feature. As for the analysis of the dynamical feature, this thesis introduces the concept of Lagrangian Coherent Structures (LCSs) developed in dynamical systems theory. Basically, LCSs are moving partitions that effectively divide the fluid domain into different regions of qualitatively different behavior (or origin or fate). The application of LCSs in biological system includes cell behavior, the blood flow mechanics inside blood vessels and hearts, etc. However most of the previous studies on biological systems were discussed by a model simulation. Here we study local-heterogeneous response and transient dynamics in colloidal fluids responding against a stimulus which might be analogous to living organisms not based on a model simulation but on observation data.

In this thesis, a system of dense driven monodisperse quasi-two-dimensional (q2d) colloidal fluids was studied. Colloidal fluids are an interesting medium that allows us to visualize some intriguing phenomena that are highly analogous to molecular liquids yet can be modulated by density or confinement to allow insight into glassy or jammed material. In this system a single particle is optically trapped at the center and gives a precise and localized mechanical perturbation to the system where bath particles are allowed to flow passing by the probe particle. Particle's responses to the perturbation are found on the space-scale of several particles diameter from the dragged particle. Indeed, these responses are spatially different at different time, and cause spatial and temporal deformation of a fluid parcel consisting of colloidal particles. How such deformations cause cage breaking and formation surrounding a reference particle is our research interest.

Quantifying the interactions in dense colloidal fluids requires a properly designed order parameter. Very frequently, the so-called bond orientational order parameter has been used to evaluate the degree of packing configuration surrounding a reference particle. In this dissertation, at Chapter 2, we first present the generalization of bond orientational order parameter around a particle in a colloidal assembly. This modified order parameter, $\bar{\psi}_6$, avoids discontinuous changes in time that has been found in the original definition of the bond-orientational order parameter. Thus our modified order parameter provides a suitable measure to quantify the dynamics of bond-orientational ordering of local surrounding. Chapter 2 also provides an introductory concept of Lagrangian coherent structures (LCSs). In this dissertation, LCSs are estimated from maximum finite-time Lyapunov exponent (FTLE) field. Indeed, this maximum FTLE gives the finite-time average of the separation (stretching/divergence) between nearby trajectories. In this chapter, we also provide how one can compute the FTLE field from a set of particle trajectories.

In a trapped particle system, a perturbation is attributed from the probe particle to a set of the neighboring particles. This perturbation indeed propagates into the flow and causes spatial and temporal distortion of the packing structure surrounding each particle. In Chapter 3, Wavelet transform provides a time-frequency representation of the time series of $\bar{\psi}_6$. From this two-dimensional scalogram plot, one can find at which time which frequency components occur in a time series. We therefore look into the frequency components that correspond to the inverse of the time scale of the perturbation. It is found that particles that have high power in frequencies we investigate the dynamics of the bond-orientational ordering of local surrounding, i.e. spatio-temporal behavior of $\bar{\psi}_6$, by a wavelet transform corresponding to the inverse of the timescale of perturbation undergo distortions of their packing configuration, yielding cage breaking and formation dynamics. Our results show that this transient cage breaking dynamics mostly appeared in the forepart of the probe particle. We find that the general time averaged spatial-correlation of the order parameter cannot identify the spatio-temporal dynamics in this system. This indicates that the use of Wavelet transform is essential in this analysis.

Chapter 3 provides a correspondence between the dynamic structure of cage breaking and formation of bond-orientational ordering and the underlying dynamical structure identified by Lagrangian Coherent Structures (LCSs). In this thesis, we show that, the language of LCSs provides a new means for studying the heterogeneous behavior in a colloidal fluid system. Particles that undergo highly disturbance by the perturbation can be identified in terms of the spatial location of LCSs. It is shown that the spatial distribution of the FTLE field and the power of particles in the wavelet transform have positive correlation, implying that LCSs provide a dynamic structure that dominates the dynamics of cage breaking and formation of the colloidal fluids.

Chapter 4 provides the conclusion and other possible application of LCSs in colloidal fluids. In this dissertation, we have analyzed Lagrangian Coherent Structures (LCSs) in a colloidal system to probe the local-heterogeneous response to the excitation elicited by the mechanical perturbation. We discuss the applicability of the concept of LCSs to provide a deep insight into the understanding of heterogeneous dynamics of, for example, collective cell migration in response to stimuli.