論文の内容の要旨

Modeling the effect of helicity on the transport of the Reynolds stress in rotating inhomogeneous turbulence

（回転系非一様乱流におけるレイノルズ応力輸送に及ぼすヘリシティの効果のモデリング）

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Most of the flow of fluids around us shows a stochastic behavior both in time and space. Such stochastic flows are referred to as turbulence. Although the instantaneous motion of turbulent fluid is stochastic and not reproducible, statistical properties such as the mean velocity or the turbulence intensity are known to be reproducible. However, the statistically averaged equations of a fluid are never closed due to the nonlinearity of the momentum equation. In order to predict the statistical properties of turbulent flows, some modeling for unclosed quantities is required. Such a modeling is referred to as the turbulence modeling.

In the equation for the mean velocity of incompressible fluid, the unclosed quantity is only the Reynolds stress, which is the auto-correlation of velocity fluctuations. The Reynolds stress represents the effect of turbulence on the mean velocity. The most primitive model for the Reynolds stress is the eddy-viscosity model, which represents the enhancement of the momentum diffusion due to the turbulent motion of a fluid. However, it is known that the accuracy of the eddy-viscosity model often decreases in the turbulent flows accompanied with rotational motion. In order to overcome this shortfall, some other effects of turbulence associated with the rotation should be considered. The vortex dynamo effect is an example which describes the effect of rotation on the mean velocity. In the previous study, the model for the Reynolds stress describing the vortex dynamo effect was proposed by considering the effect of the turbulent helicity, which is the statistical average of the inner product of velocity and vorticity fluctuations. The previous study numerically showed that the mean velocity is generated in rotating turbulence accompanied with the turbulent helicity. This mean velocity generation phenomenon is consistent with the previously proposed model for the Reynolds stress accompanied with the turbulent helicity. However, the mechanism that the turbulent helicity affects the mean velocity or the Reynolds stress has been unclear.

There is another shortfall of the conventional turbulence model in rotating turbulence. The previous studies of rotating turbulence showed that the kinetic energy of turbulence is transferred faster in the direction of the rotation axis than non-rotating case. It was shown that the turbulence region d grows as $d \sim t$ in the rotating case, while $d \sim t^{1/2}$ in the non-rotating case. Hence, this energy diffusion cannot be predicted by the gradient diffusion approximation, which predicts that the growth of the turbulence region as $d \sim t^{1/2}$. In the conventional turbulence modeling, the turbulent energy flux is modeled by the gradient-diffusion approximation, so that it cannot predict the fast energy transport observed in rotating turbulence. The previous study suggested that this fast energy transport is explained in terms of inertial wave described by the linearized momentum equation in a rotating system. It is known that the propagation direction of the group velocity of inertial waves is related to the sign of helicity. This fact suggests that the fast energy transport in the direction of the rotation axis can be modeled in terms of the turbulent helicity.

In order to investigate the effect of the turbulent helicity on the mean velocity, the numerical simulation of rotating turbulence in which the turbulent helicity is injected by using the external forcing is performed. Similar to the previous study, the mean velocity in the direction of the rotation axis is generated only when the system is rotating and the turbulent helicity is injected. The budget for the transport equation for the Reynolds stress is investigated to clarify the source of the mean velocity. It is shown that the pressure diffusion term, which is the spatial derivative of the correlation between velocity and pressure fluctuations, has a significant contribution to the mean velocity generation phenomenon. It is revealed that the pressure diffusion can be expressed by the turbulent helicity. A new turbulence model for the pressure diffusion accompanied with the turbulent helicity is proposed by means of the statistical closure theory which is referred to as the two-scale direct interaction approximation (TSDIA). It is also shown that the previously proposed model for the Reynolds stress accompanied with the turbulent helicity can be obtained based on the Reynolds stress transport equation by incorporating the effect of the pressure diffusion. The model for the Reynolds stress accompanied with the turbulent helicity can account for the mean velocity generation phenomenon without contradiction to the simulation results. Since the pressure diffusion is conventionally neglected in the previous turbulence modeling, the present result points out the critical shortfall of the conventional turbulence model in rotating turbulence accompanied with the turbulent helicity.

In order to investigate the turbulence model predicting the fast energy transport phenomenon observed in rotating turbulence, the numerical simulation of decaying inhomogeneous turbulence in rotating system in which the turbulent energy is diffused in the direction of the rotation axis is performed. It is shown that the pressure diffusion term associated with the rotation significantly contributes to the energy transport in the rotating system. The newly proposed model for the energy flux accompanied with the turbulent helicity accounts for the spatial distribution of the energy flux due to the pressure associated with the rotation, which cannot be explained by the gradient-diffusion approximation. It is shown that this energy flux due to the rotation is tightly connected to the group velocity of inertial waves described by the linearized momentum equation in a rotating system. Finally, the helical Rossby number is proposed to judge the significance of the energy flux due to the turbulent helicity and rotation in general turbulent flows.