論 文 の 内 容 の 要 旨

論文題目　High-order semi-Lagrangian type Vlasov solver for ion flow simulation in Hall thrusters
（ホールスラスタにおけるイオン流れの計算のための高次精度セミラグランジュ型ブラソフ解法）

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Hall thruster (HT), a widely used electric propulsion (EP) device used for spacecraft propulsion, employs a cross-field configuration with a radial magnetic field and an axial electric field. A critical issue for HT is the discharge current oscillations. HTs are well known to exhibit fluctuations of several types in a wide frequency range. These fluctuations are closely related to the performance and plasma characteristics of HTs. For plasma sources, the fluctuation with the largest discharge amplitude observed is the ionization oscillation, which may affect the weight of power processing unit (PPU).

Several numerical models have been developed for modelling discharge current oscillation phenomena. Heavy species with a large Knudsen number in plasma, such as ions and neutrals, are usually solved through the kinetic models. The full particle-in-cell (PIC) model combined with Poisson’s equation for space potential is often used to analyses plasma fluctuations in HTs. However, hybrid PIC-fluid models that treat electrons as a continuum fluid are also used widely for the numerical simulation of HTs. One demerit of the kinetic particle model for the heavy species is the statistical noise attributable to the small number of macroparticles handled in the simulation. During analyses of discharge oscillations, these numerical noises might interfere with physical oscillations, leading to inaccurate analysis.

In this dissertation, a high-resolution noiseless ion-Vlasov solver is developed for the analyses of discharge current amplitude in HTs. The objective of this research is to develop an alternative Vlasov solver which can replace the particle-in-cell (PIC) solver in the hybrid model to achieve a noiseless result. The Constrained Interpolation Profiles Conservative Semi-Lagrangian method with a third-order reconstruction polynomial (CIPCSL3) method with Strang splitting is employed to solve the Vlasov equation. To keep the spatial high resolution, a fourth-order weighted essentially non-oscillatory limiter is used for the first derivative.

The fourth-order CIPCSL3 method and high resolution Vlasov solver are verified through several test cases with analytical solution, the calculation results are compared with a second-order TVDCW scheme as a reference. All schemes achieve the design order of accuracy for one-dimensional and two-dimensional test problems with analytical solution, and the fourth-order WENO scheme shows the fastest convergence speed. For the test case with discontinuities, fourth-order scheme shows high resolution in the region near the sharp profile gradient without generating unexpected numerical oscillations.

The Vlasov equation solver is successfully developed by using CIPCSL3 method with fourth-order WENO limiter, the applicability of VP system is confirmed by solving the Landau damping and two stream instability problems. In the weak linear Landau damping case, both of fourth order WENO limiter and second-order TVDCW limiter predict the damping rate correctly, and in the strong nonlinear Landau damping case, the fourth-order WENO scheme predicts the damping and growth mode correctly, the results are compared with other literatures. On the other hand, the low order scheme fails to capture the growth mode. In the two stream instability case, the design spatial accuracies of the schemes are confirmed.

The results of two stream instability generated by fourth-order Vlasov solver also have been compared with PIC solver. The fourth-order CIPCSL3 Vlasov solver generates a noiseless result compares with the PIC solver, it also shows a high-resolution feature to capture the symmetric profile in low-density region, on the other hand, the PIC solver fails to solve the symmetric profile.

Finally, the high-resolution fourth-order CIPCSL3 Vlasov equation solver is combined with the electron fluid model to analyses the discharge current oscillation in HTs and compared the results with hybrid PIC solver. For a single velocity bin calculation in one cell, the hybrid Vlasov-fluid solver shows the computational cost about eleven times higher than a single macroparticle calculation in one cell of the hybrid PIC solver. But owing to the feature of high resolution, the hybrid Vlasov-fluid solver generates the convergence result by employing 192 grids in velocity space per cell, on the other hand, the hybrid PIC solver needs 6000 macroparticles per cell to achieve a reasonable convergence result. The thruster performance and time-averaged plasma properties generated by the hybrid Vlasov-fluid solver show a good agreement with hybrid PIC solver's result. For the discharge current amplitude analyses, the hybrid Vlasov-fluid solver shows a widely calculation range along with different maximum magnetic flux density. The results predict the minimum oscillation amplitude occurs with classical diffusion coefficient near $B_{r,max}$=13 mT, and the trends of oscillation amplitude are the same as hybrid PIC solver obtained.