Particle Simulation Analysis by Virtual Reality System

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Introduction

Virtual Reality
Introduction

• Simulation research
  – Modeling
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• Computer technology is rapidly advanced.
• Simulation size becomes larger and larger.
• 3-dimensional simulation is commonly performed.
  ->Simulation results become more complicated.
  ->Data size also becomes massive.

• Analyzing is a key issue in simulation research.
• Bringing out useful physical information from the massive simulation data is important.
• More effective analysis method is demanded.
Problem in 2-D Scientific Visualization

3-D visualization by polygon (surface, streamline, contour and so on)
  -> Understanding the structures of physical quantities of 3-D data.
3-D objects by polygon have to be projected on 2-D display.
  .When the structure of objects by polygon is simple,
  -> Easy reconstruction of 3-D structures in your brain.
Problem in 2-D Scientific Visualization

Projection of the particle trajectories, or magnetic field stream lines on the 2-D display
-> Difficult to grasp the structures because of lack of the depth information.
Problem in 2-D Scientific Visualization

3-D Simulation Data should be Analyzed in 3-D Space!!

Scientific Visualization by 3-D Virtual Reality System (CAVE System)
CompleXcope (CAVE VR system) in NIFS

Stereoview on 4 screens by liquid crystal glasses
Immersive view in the room composed of 4 screens
Interactive view by tracking system and 3D mouse.

Viewer with liquid crystal glasses comes into the room, he is surrounded by 4 screens. When he moves his head or walks in the room, the images on the screens are reconstructed rapidly according to his movement by tracking system.

*Viewer feels himself being in the simulation model, and he can watch the objects with any size and from all directions.*
Application to Magnetic Reconnection Research
Application to magnetic reconnection research

- **Magnetic Reconnection**
  - Solar corona, magnetosphere substorm and tokamak discharge.
  - Fast energy release from magnetic field to plasmas, and change of the field topology.
  - Microscopic phenomena
    - Generation of electric resistivity (wave-particle interaction, a binary collision, and so on)
  - Macroscopic phenomena
    - Topological change of magnetic field, global plasma transport and so on.
Violation of Frozen-in constraint
(PIC simulation result)

Force balance equation

\[ q^i n^i \left( E + u^i \times B \right)_z = m^i n^i \left\{ \frac{\partial}{\partial t} + \left( u^i \cdot \nabla \right) \right\} u^i_z + \nabla \cdot \tilde{P}^i \]

Ion \( \omega_{ci} t = 805, m_i / m_\varpi = 100 \)

\[ E_z = -(u^i \times B)_z \]
\[ \frac{\nabla \Pi}{q^i n^i} \]
\[ m^i (u^i \cdot \nabla) u^i_z / q^i \]

\( L_m \) : Meandering Orbit Amplitude

Ion: pressure tensor term sustains reconnection electric field

Meandering (non-gyration) motion near neutral sheet

Larmor radius $\rho_L \propto \frac{1}{B(x)}$

meandering orbit amplitude:
local Larmor radius = distance from neutral sheet ($\rho_L(x) = x$)

Charged particles make a bounce motion across the neutral sheet, and mix the plasmas with different origins \( \rightarrow \) a microscopic cause of electric resistivity
Meandering (non-gyration) motion near neutral sheet

Larmor radius $\rho_L \propto \frac{1}{B(x)}$

$y = \rho_L(x)$  

Relationship between complex particle trajectories and reconnection mechanism directly.

Charged particles make a bounce motion across the neutral sheet, and mix the plasmas with different origins $\rightarrow$ a microscopic cause of electric resistivity
Analysis of Particle Trajectories in 3-D VR space.

- Enormous data of particles by PIC simulation.
- It is impossible to store all of them!
- It is difficult to find the particle which passes the reconnection region.

- We store the field data in HDD.
- The equation of motion for particle are solved in the electromagnetic field obtained from PIC simulation.

  => Investigation of particle trajectory in VR space.
VFIVE + Particle trace

- General purpose VR visualization software: VFIVE
  - You can download from http://www.jamstec.go.jp/esc/research/Perception/vfive.en.html

- Vector field
  - Lines, arrows and so on.

- Scalar field
  - Contour, isosurface, and volume rendering.

- Improvement for tracing particles in the electromagnetic field obtained by PIC simulation.
  - The equation of motion for a single particle
    - Newton-Lorentz equation
    - Leap-frog method
  - Electromagnetic field (B, E) on the grid points
    - From the results of PIC simulation
    - Force acting on the particles by third-order interpolation of fields at the nearest grid points
  - Initial condition of the particle
    - Position: Indication by Wand (3D mouse, Interactive)
    - Velocity: Maxwellian distribution + Average velocity (=Flow velocity by simulation data)
Results(1)

Analysis of magnetic reconnection simulation data in CompleXcope.
• In usual talk about VR technology, I have no way except presentation with traditional projection on 2D screen, because I can not bring the CAVE system there.

• Today, this workshop is held at NIFS!!!
• You can touch directly VR world.
• Seeing is believing!
• Tour of VR and Supercomputer System in NIFS
  – Tuesday 5pm-5:40pm
Results (2)

- CAVE visualization of magnetic structure (lines, arrows, and color contour) and density profile (isosurface and color contour)

CAVE visualization of magnetic structure (blue lines), ion temperature profile (color contour), ion flow velocity (arrows) and trajectories of ions (white line).

Results(4)

<-CAVE visualization of magnetic field line (blue lines), reconnection component of field (color contour in yz plane), ion temperature profile (color contour in xy plane), and trajectories of ions (white lines).

Ions coming from upstream execute meandering motion. Amplitude of orbits ≈ width of high temperature region Reconnection component of field: wavy structure (DKI).

More advanced VFIVE

- These visualization results by one-snapshot simulation data, and the particle movements under the fixed field.

- Plasma instabilities are excited in the reconnection region.
- What is effect of time-changing electromagnetic field on particle trajectories?

- More improvement is needed for tracing particles in the time-dependent electromagnetic field obtained by simulation.
- Field data are stored every several time-steps when simulation is performed.

- Animation function using the stored data!
VFIVE: Animation

1. After visualizing his data in CAVE interactively, user activates “Animation function”.
2. VFIVE reads the next data from HDD and visualizes them with the same parameters (ex., isosurface levels), and saves the polygonal data of the objects (ex., isosurface) as a macro of OpenGL called “Display list” (or to HDD when the number of time steps is large).

VFIVE: Animation

3. After saving the polygonal data of all time steps, VFIVE begins to display them in CAVE one after another.

4. In this animation function, field data are updated in VR space every $\delta T$.

5. Field data from simulation results are stored every $100\Delta t$ ($=\delta T$).

   => Field data are updated in VR space every $100\Delta t$.

   Newton-Lorentz equation is integrated by $\Delta t$ in the updated field data every $100\Delta t$ ($\omega_{ce} \Delta t = 0.07$: Simulation time step).
Results (5)

- CAVE visualization in time-varying case of magnetic field line (blue lines), reconnection component of field (color contour in yz plane), ion temperature profile (color contour in xy plane), and trajectories of ions (white lines).
Results (6)

Snap shot data: Different trajectories between snap-shot and time-dependent data.

Particles moves faster along outflow direction in the case of time-dependent data.

Time-dependent field has effect of acceleration along outflow direction?
Summary

• We introduced three-dimensional and four-dimensional analysis methods in VR space.

• We modified VFIVE in order to study particle kinetic effects in plasma. Particle trajectories in the electromagnetic fields obtained by simulation can be shown in VR space.

• We added animation function to VFIVE to analyze temporal evolution of field data and particle trajectories in VR space.

• We applied this software to investigation of magnetic reconnection.
  – It is clearly demonstrated that particle kinetic effects are strongly related to the triggering of magnetic reconnection and heating mechanism.
  – In the case of temporary evolving electromagnetic field, particle is more accelerated along outflow direction than in the case of fixed electromagnetic field.

• This software can be widely applied.
  – Data by another type of simulation can be also loaded.
  – Equation of motion for particle can be replaced to another equation (guiding center, etc).

• VR technology is a very useful tool in simulation data analysis.