MHD Study on Pure Magnetic Sail

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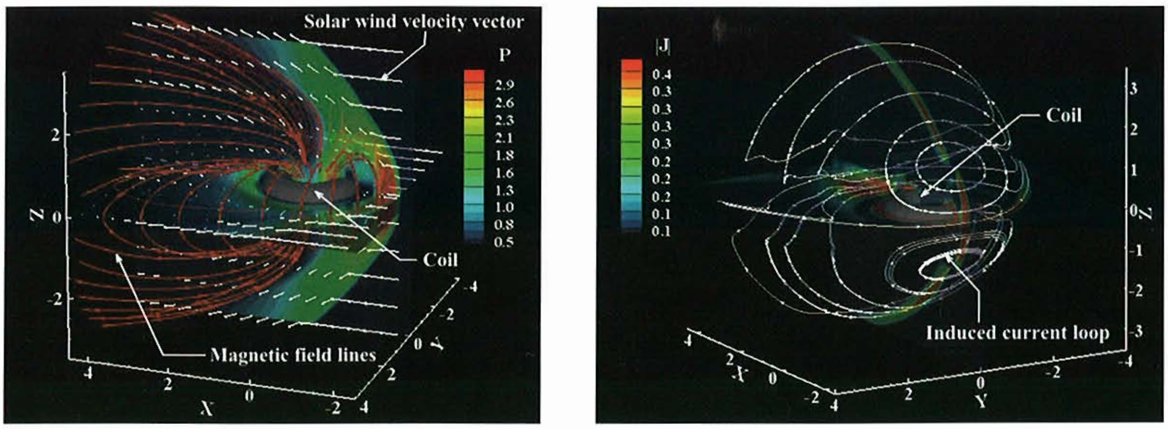
Magnetic Sail is a deep space propulsion system which captures the momentum of the solar wind by a large artificial magnetic field produced around a spacecraft. To verify the momentum transfer process from the solar wind to the spacecraft, we simulated the interaction between the solar wind and the artificial magnetic field of Magnetic Sail using magnetohydrodynamic model. The result showed the same plasma flow and magnetic field structure as those of the Earth. The change of the solar wind momentum results in a pressure distribution on the magnetopause. The pressure on the magnetopause is then transferred to the spacecraft through the Lorentz force between the induced current along the magnetopause and the current along the coil of the spacecraft. The simulation successfully demonstrated that the solar wind momentum is transferred to the spacecraft via the Lorentz force. The drag coefficient (thrust coefficient) of the Magnetic Sail was estimated to be 5.0.

Figure 1: Flow field and magnetic field around Magnetic Sail (A), and induced currents around Magnetic Sail (B).

(A) **(B)**



JAXA/JEDI workshop on numerical plasma simulation for spacecraft environment

MHD Study on Pure Magnetic Sail

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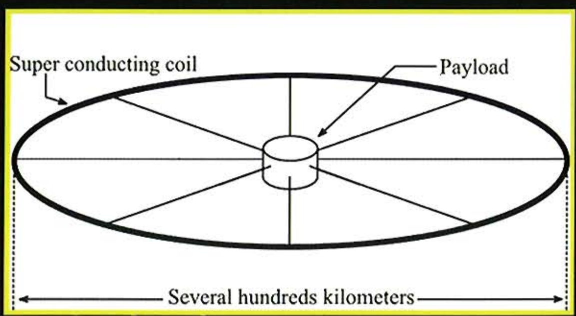
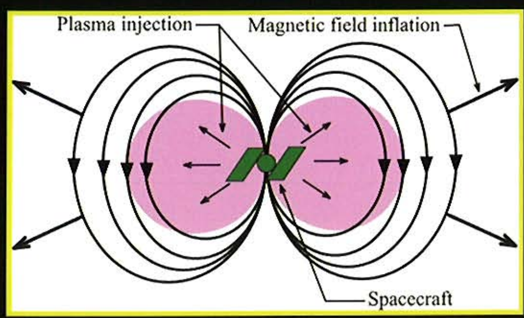
Magnetic Sail and Magneto Plasma Sail (MPS)

- Propulsion systems generating thrust through the interaction between the solar wind and the magnetic field produced around the spacecraft.



Magnetic Sail



Magneto Plasma Sail (MPS)
(M2P2)

- Magneto Plasma Sail is a more realistic propulsion system.

Previous researches

Some numerical researches about thrust generation mechanism and performance of those propulsion systems by kinetic model of ion

- Hybrid code; Khazanov, Omidi, Saha, et al ….
- Particle-in-Cell code; Fujita, et al ….

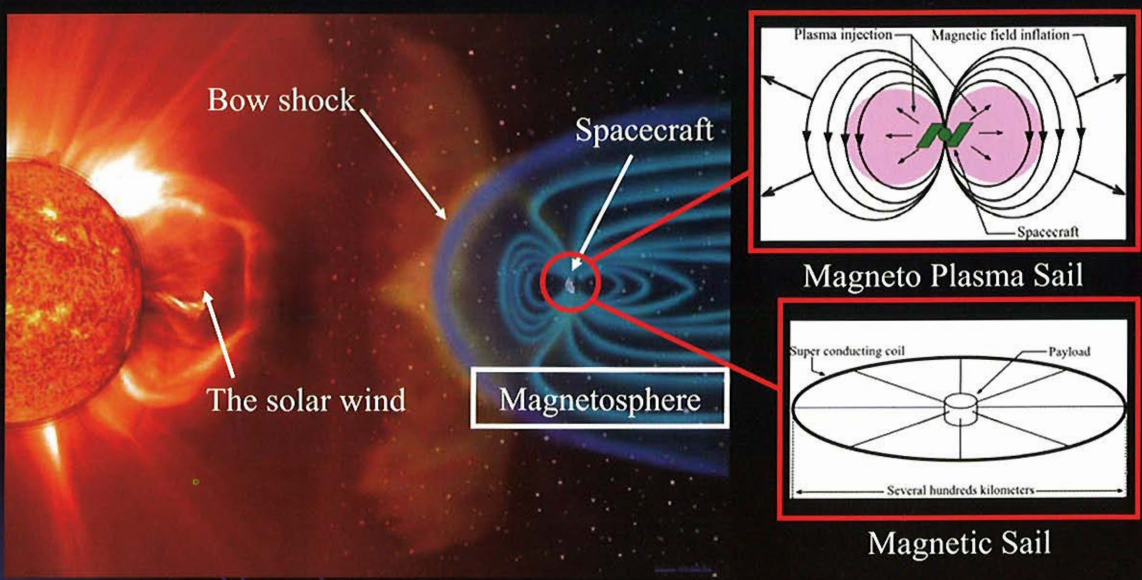
Research based on magnetohydrodynamics (MHD) is needed, too.

Because …

- ➤ The small interaction in kinetic scale of ions generating only small thrust
- ➤ Kinetic simulation needs high numerical cost.

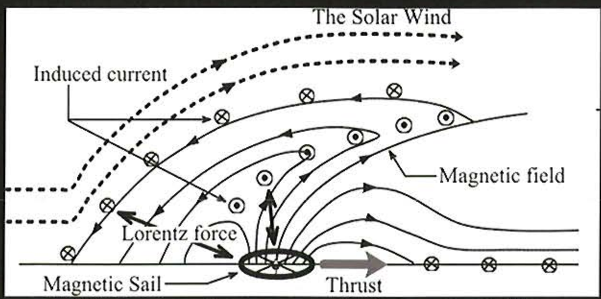
- Researches based on MHD; Winglee, Zubrin, ….

Principle of propulsion

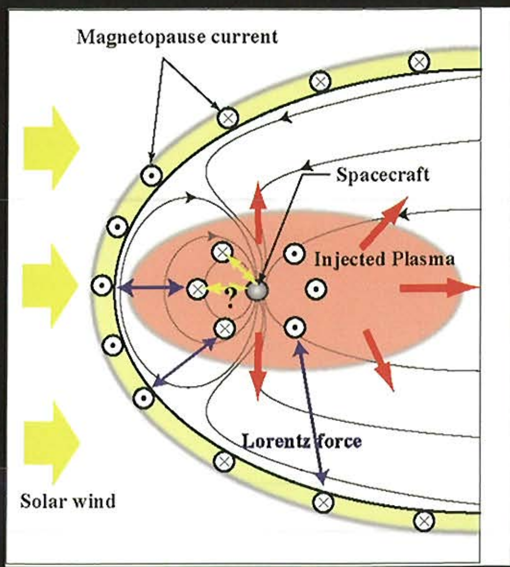


Interaction between the solar wind and the magnetic field around the spacecraft

Principle of propulsion



Magnetosphere around Magnetic Sail



Magnetosphere around Magneto Plasma Sail

- **Momentum of the solar wind is transferred to the spacecraft through electromagnetic interaction**

Objectives

In this study, the interaction between the solar wind and the magnetic field of Magnetic Sail is simulated based on magnetohydrodynamics.

- By two-dimensional MHD simulation,
  - identifying action and reaction forces and their balance in order to verify the momentum transfer process.
- By three-dimensional MHD simulation,
  - estimating the thrust vector and the torque on the Magnetic Sail.

Governing Equations and Numerical Methods

- Normalized ideal magnetohydrodynamic equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} + p\mathbf{I}) = \mathbf{J} \times \mathbf{B}$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) = 0$$

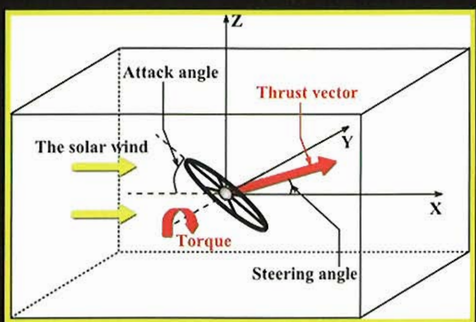
$$\frac{\partial E}{\partial t} + \nabla \cdot \left[\left(E + p + \frac{B^2}{2} \right) \mathbf{v} - \mathbf{B}(\mathbf{B} \cdot \mathbf{v}) \right] = 0$$

$$\mathbf{J} = \nabla \times \mathbf{B}$$

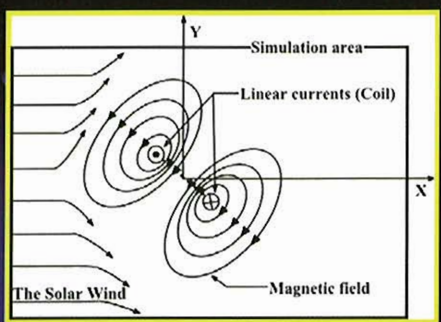
t : time
ρ : density,
p : pressure,
$\mathbf{v}$: velocity vector,
$\mathbf{B}$: magnetic flux vector,
$\mathbf{I}$: unit matrix,
$\mathbf{J}$: current vector,
E : energy density.

- Numerical method:
  - Flux-Corrected Transport (FCT) scheme
  - TVD Lax-Friedrich scheme with 8-wave formulation

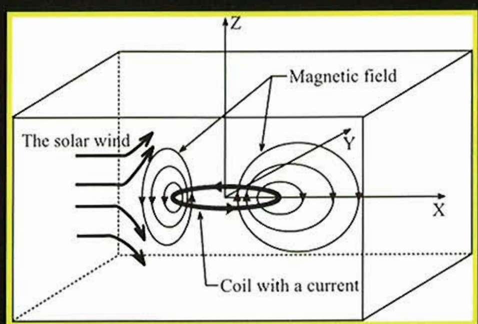
Computational Models



The definition of the coordinate system.



Simulation box of two-dimensional simulation.



Simulation box of three-dimensional simulation.

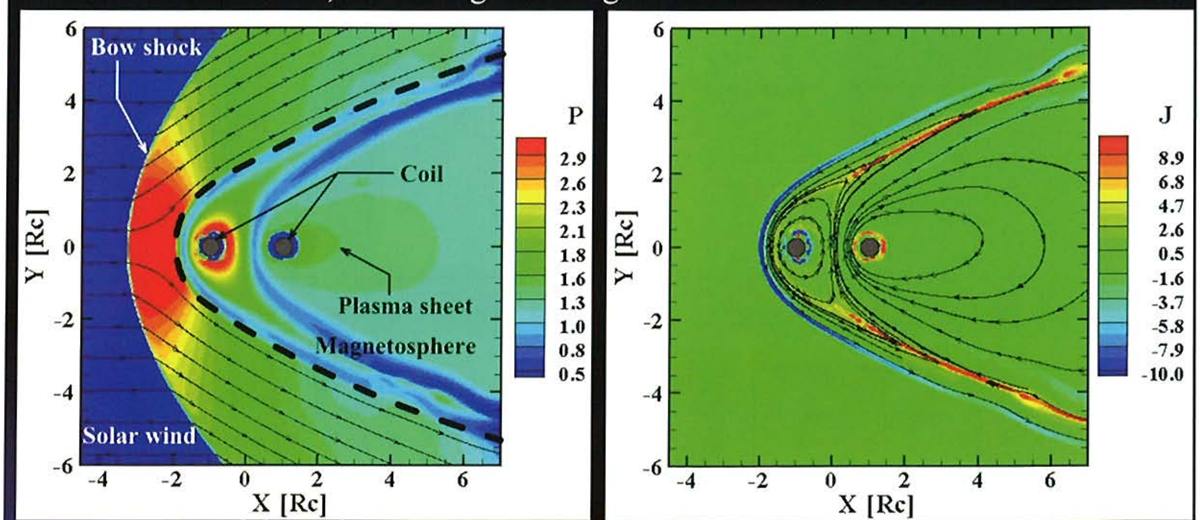
Computational Parameters

Solar wind velocity	0.917 (400km/sec)	
Solar wind pressure	8.68×10 ^{2} (20 eV)	
Solar wind density	5.0 ($5m_i \times 10^6$ kg/m^3)	
IMF	0 T	
Coil currents	1.2×10^{12} In 2D simulation	9.6×10^{12} In 3D simulation
Attack angle	0 ～ 90 deg	
Simulation area	-5<X<7, -6<Y<6 In 2D simulation	-2.5<X<4.5, -4<Y<4, -3.5<Z<3.5 In 3D simulation

(In normalized value)

Two-dimensional Simulation – Flow Field

Rc = radius of the coil, attack angle = 0 degrees

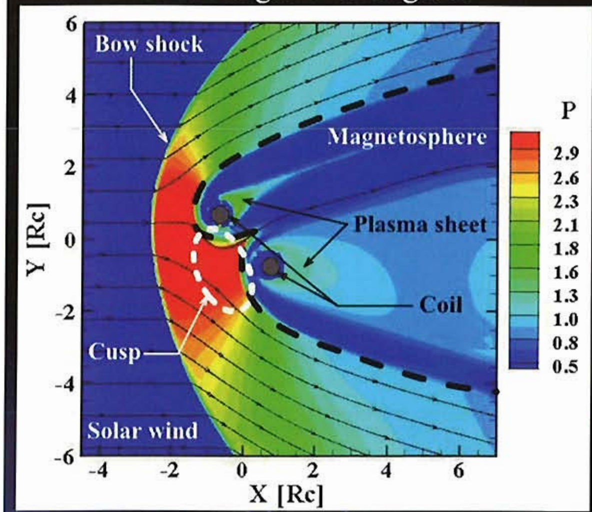


Pressure contours and streamlines

Induced current contours and magnetic field lines

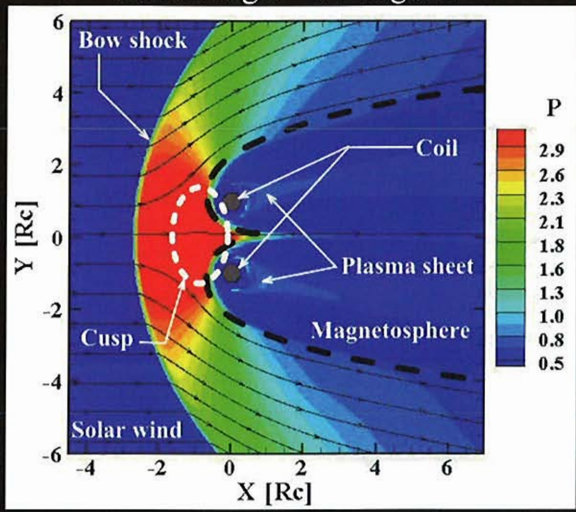
Two-dimensional Simulation – Flow Field (2)

Attack angle = 45 degrees



Pressure contours and streamlines

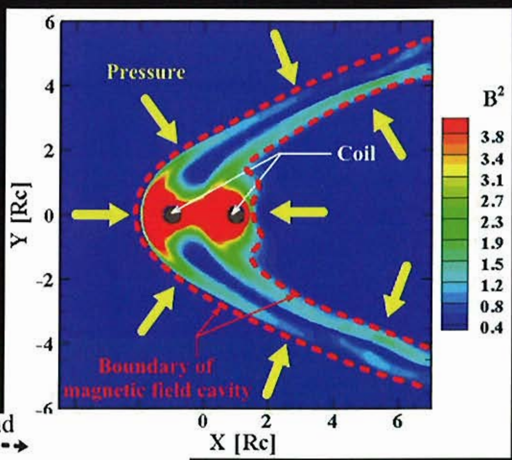
Attack angle = 90 degrees



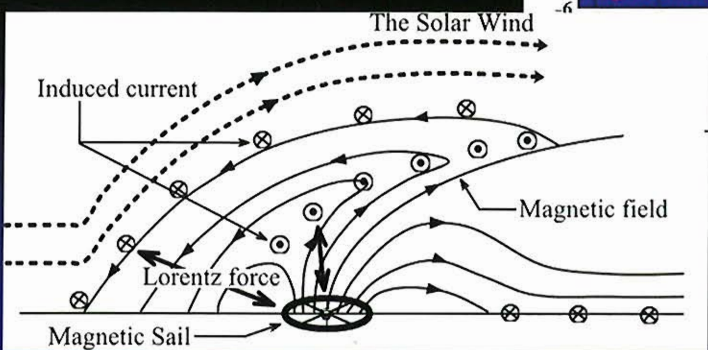
Pressure contours and streamlines

Identifying action and reaction forces

- F1: Momentum change of the solar wind.
- F2: Force acting on the magnetosphere by the solar wind pressure.
- F3: Lorentz force between the induced current and the coil's current.

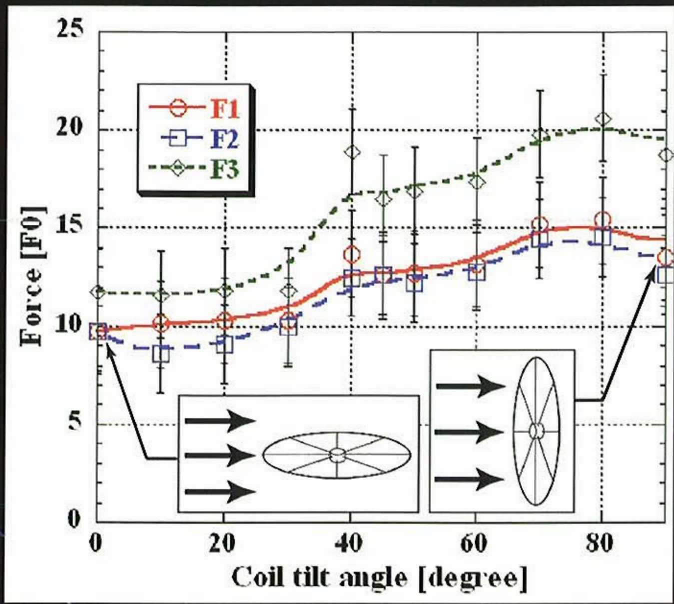


The magnetic field intensity contours and the magnetic field cavity pressed by the solar wind pressure



Lorentz force between the induced current and the coil's current (F3)

Evaluation of forces

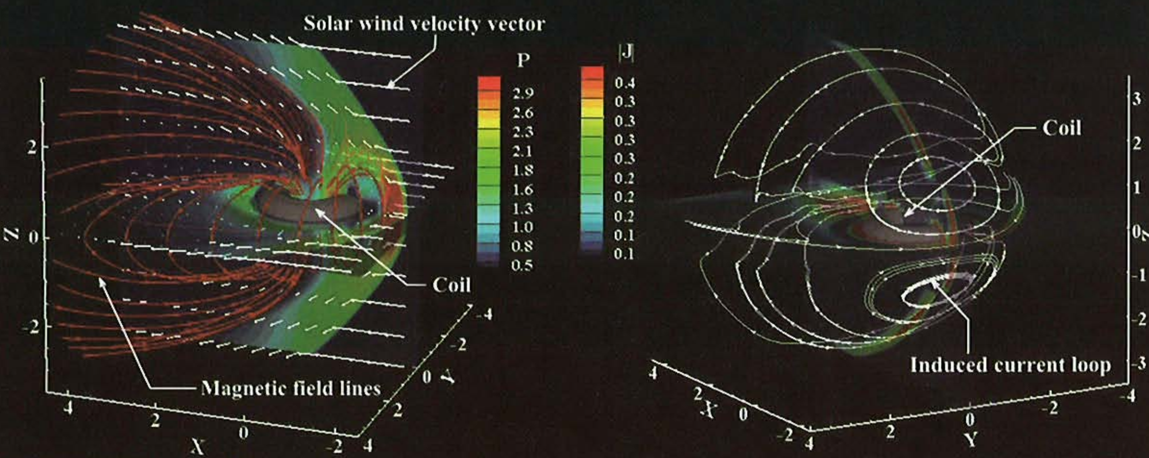


The relation between the attack angle and forces in normalized value

- Each force is of the same order and in same trend. These three forces are the same.

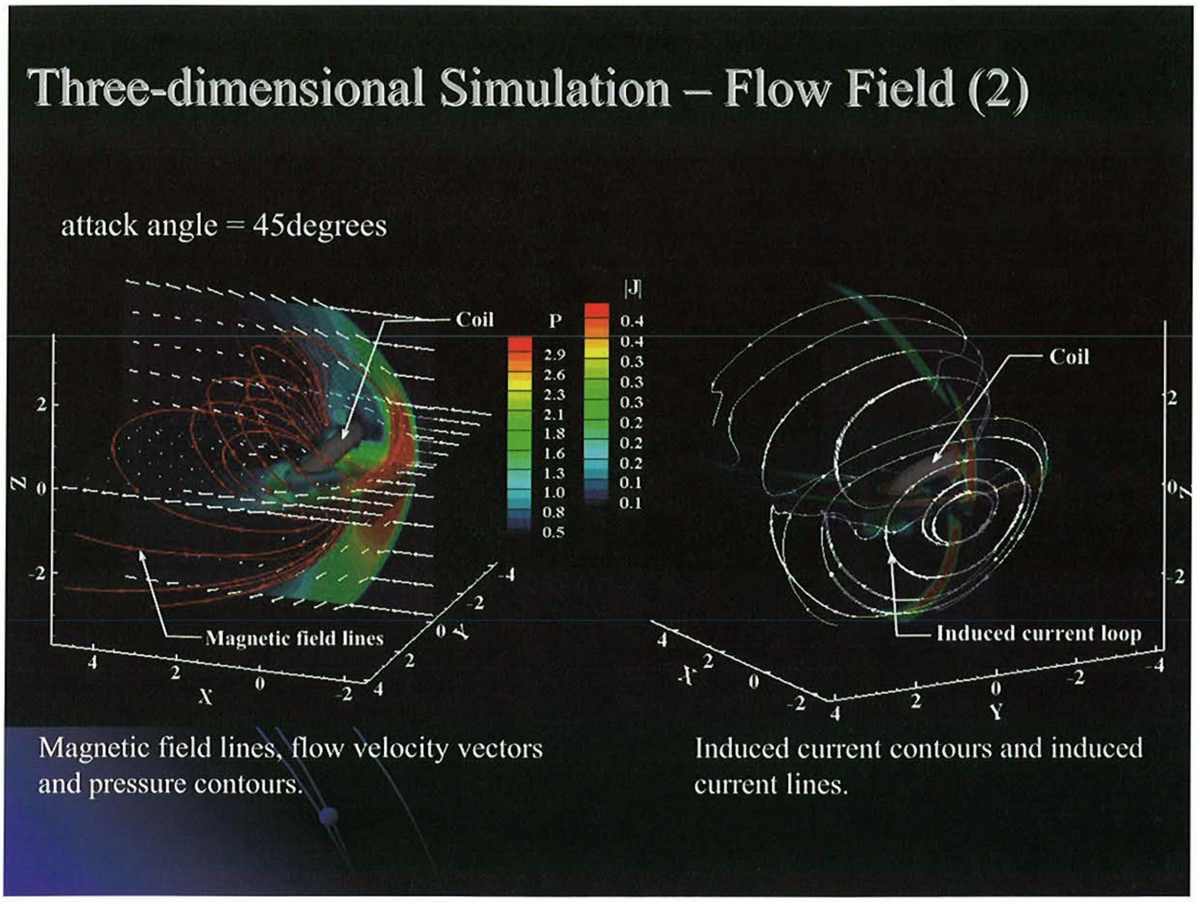
Three-dimensional Simulation – Flow Field

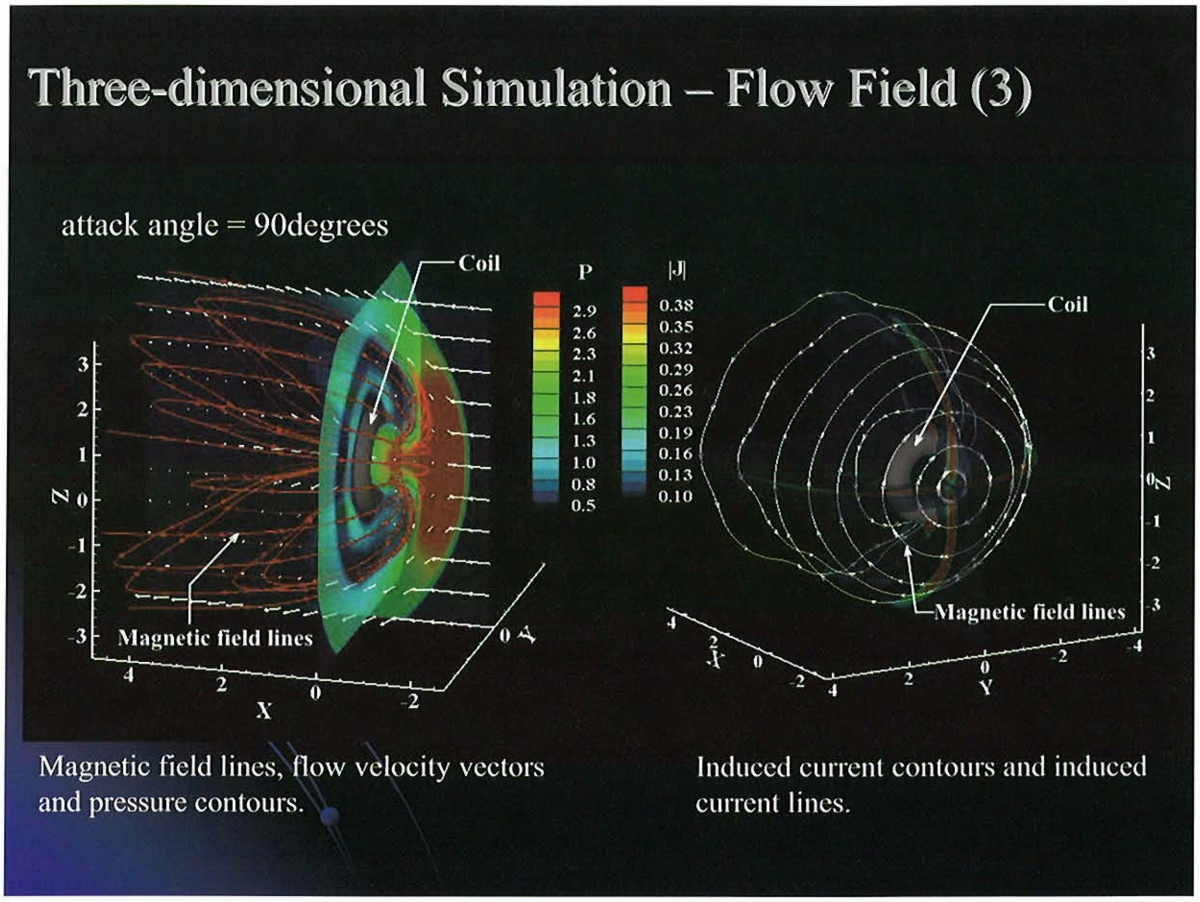
attack angle = 0degrees



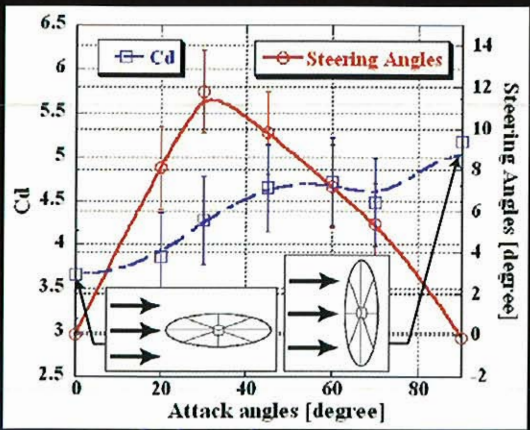
Magnetic field lines, flow velocity vectors and pressure contours.

Induced current contours and induced current lines.

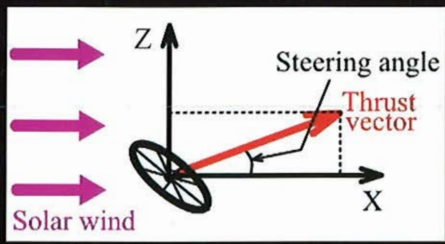

Three-dimensional Simulation – Flow Field (2)
attack angle = 45degrees
Coil
P
|J|
Magnetic field lines
Induced current loop
X
Y
Z
Magnetic field lines, flow velocity vectors and pressure contours.
Induced current contours and induced current lines.


Three-dimensional Simulation – Flow Field (3)
attack angle = 90degrees
Coil
P
|J|
Magnetic field lines
X
Y
Z
Magnetic field lines, flow velocity vectors and pressure contours.
Induced current contours and induced current lines.

Thrust vectors



The relation between attack angle and the thrust vector.

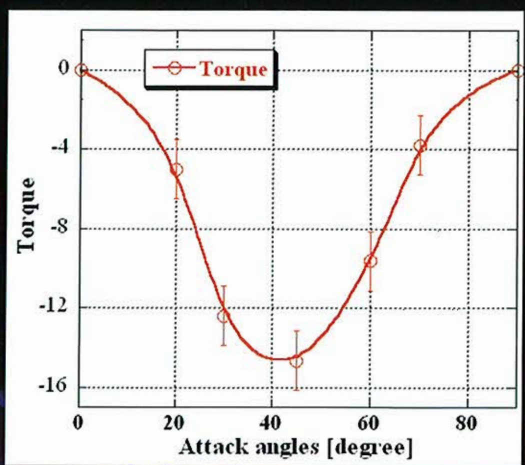


Drag coefficient $C_d = D / \left(\frac{1}{2} \rho v^2 S_c \right)$: $S_c = \pi r_r^2$

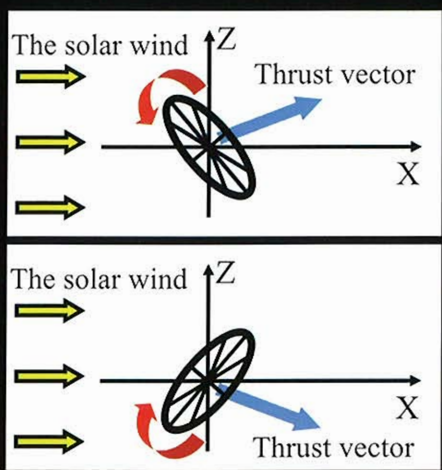
r_r = shock stand off distance from the center of the coil.

- Highest thrust in 90 degrees.

Torque



The relation between attack angle and the torque.



- Magnetic Sail has static stability around 0 degrees in attack angles.

The validity of MHD assumption

The scale of Magnetic Sail

Radius of the coil [km]	Current in the coil [kA]	Thrust [N]	Max Torque [N.m]	rLi/rr	MHD validity
10	4	2.25	4.5k	1.25	×
20	8	9	36k	0.625	△
40	16	36	284k	0.315	△
100	40	225	4500k	0.125	○
200	80	900	18000k	0.0625	○

- When rLi/rr＜＜1, MHD validity satisfied.
- In this simulation, when radius of the coil > 100km, MHD assumption is valid.

Summary

The Magnetic Sail was simulated based on magnetohydrodynamcis to verify the momentum transfer process, and to estimate the thrust vector and the torque.

- The simulation successfully demonstrated that the change of the momentum of the solar wind is transferred to the spacecraft via the Lorentz force.
- The maximum drag coefficient (thrust coefficient) is estimated to be 5.0 when the attack angle is 90 degrees.
- Maximum steering angle is estimated to be 12 degrees when the attack angle is 30 degrees.
- Magnetic Sail can control the thrust vector by changing the attack angle, but cannot maintain a constant attack angle without dynamic attitude control due to the static stability.