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博士論文の要旨

氏　　名　村山　裕輝

論文題目　　電磁流体解析による磁気プラズマセイルの推力拡大機構解明と磁気圏現象

A magnetetoplasma sail, MPS was proposed as future propulsion system to achieve massive and low-cost round-trip interplanetary transportation and deep space exploration. A magnetic sail is a propulsion system that produces thrust by the magnetosphere formed by the interaction between charged particles of the solar wind, which is a plasma flow constantly flowing out from the sun, and the magnetic field of the spacecraft’ s onboard coil. To obtain several newtons thrust from the coil only, it is necessary to increase the coil size. Therefore, the thrust-to-weight ratio becomes small. To solve this problem, MPS was proposed, in which the spacecraft is equipped with a plasma injection source to increase thrust by actively magnetospheric inflation. The propulsive performance of MPS is evaluated by the absolute value of thrust, but also by the thrust gain, which is the rate of increase thrust after plasma injection compared without plasma injection.

The use of MPS spacecrafts for the large-scale interplanetary transportation and the deep space exploration is possible on only huge scales with a large absolute value of thrust. Future technology is making it possible to design large spacecraft of several kilometers in size. For large-scale round-trip transportation systems in space, specific impulse and thrust-to-weight ratios that exceed those of existing electric propulsion systems will be required to be achieved. The reason is that the MPS must have a system weight advantage over clustered electric propulsion systems. As typical performance values of ion engines, which are considered most suitable for deep space exploration due to their high specific impulse among existing electric propulsion systems, a specific impulse of 3000-5000 s and a thrust-to-weight ratio of 1 mN/kg are assumed. The performance of MPS is targeted to exceed that of electric propulsion in specific impulse and to be comparable to electric propulsion in thrust-to-weight ratio. To produce such propulsive performance with MPS, the scale must be enormous, and a numerical simulation approach must be prioritized over experimental demonstration. MHD analysis can evaluate the magnetospheric structure consisting of interaction between the solar wind and the magnetosphere on a macro scale, including the magnetospheric interface currents directly related to thrust production, and the low computational cost allows many surveys with varying condition settings. Therefore, in this study, MHD analysis was performed for a magnetosphere size of 100 kilometer-class MPS, with coils of several tens kilometer.

Our MHD analysis was based on ideal magnetohydrodynamic equations. The

numerical grid is a two-dimensional axisymmetric model. However, the finite volume method was used to discretize this equation. This is to accurately evaluate the momentum of the fluid flowing into and out of each cell and to calculate the thrust. The dipole magnetic field was given as an initial condition. The plasma injection regions were located near the spacecraft and the injection plasma arranged at a set pressure as the initial condition. The plasma pressure was defined as the thermal and dynamic pressures normalized by the magnetic pressure at the plasma injection region, respectively β_{th} and β_{k}. However, the injection velocity that determines β_{k} is the velocity from the center outward in the radial direction. Magnetospheric inflation mechanisms can be either caused from thermal pressure or dynamic pressure. Many of the previous studies focused only on the effects of either of those. The magnetospheric phenomena caused by two kinds of pressure will clarify the mechanism of thrust increase and saturation, and a parameter survey of thrust gain distribution and magnetospheric structure for each injection plasma parameter was conducted.

This dissertation is composed of eight chapters. Chapter 1 is the introduction. Chapter 2 describes the numerical methods in detail. In Chapter 3, we evaluate the validity of the MPS calculations based on the MHD calculations performed in this study in terms of the calculation method. And the calculation results are also compared with scale model experiments. Chapter 4 investigates the effects of variations in thermal and dynamic pressures of the injection plasma on thrust performance and magnetospheric structure at different injection angles. Chapter 5 investigates the effects of plasma injection pressure characteristics on thrust performance and magnetospheric structure. In chapter 6, the full-scale spacecraft weight and thrust performance estimate was investigated with the view to the parameters obtained from the calculations. Chapter 7 is discussions. The relationship between magnetospheric structure and plasma injection based on Chapters 4 and 5 is shown. And, based on the obtained the spacecraft design, the applicability to the Earth-Asteroid belt round-trip transportation mission was discussed. Chapter 8 showed the conclusion remarks.

Chapter 4 shows the survey results and discussion, focusing on the relationship between the direction of plasma injection and the thermal and dynamic pressures. There are two types of induced currents generated in the magnetosphere: one is due to thermal pressure and the other is due to dynamic pressure. The current is induced by the interference between the pressure and the magnetic field. When the dipole poles are parallel to the solar wind flow, the direction perpendicular to them is defined as zero degree. For the plasma is injected at zero degree, the induced currents can efficiently enhance the ring currents without generating induced currents that interfere with the magnetopause currents. The value was close to double the thrust gain, the largest in the previous studies. For non-zero-degree injection, the thrust was lower than for zero degree injection because the current that weakens the ring current is enhanced for any increase in either β_{th} or β_{k} for the same angle. In particular, the thrust gain was less than one when the injection angle was more than 30° . It was confirmed that the induced current by injection plasma cancelled the magnetopause current. For conditions such as $\beta_{th}<0.2$, the development of ring current by diffusion is weak, so that when the plasma is injected at an angle of about 10° degrees, the thrust exceeds that of zero-degree-injection because the injected plasma is spread out into the magnetosphere. However, in terms of thrust per energy input, the zero-degree-injection is superior.

Chapter 5 shows an evaluation of the relationship between thrust and magnetospheric structure for a combination of thermal and dynamic pressure in the injection plasma. We clarify the mechanism in which the dynamic pressure of the injected plasma relieves the plasma stagnation near the spacecraft and extends the plasma that generates the ring current in the direction perpendicular to the solar wind, promoting the development of the ring current due to the thermal pressure. As a result, a thrust gain of 2.3 was achieved, which is higher than the 1.9-2.2 in the previous study. Next, we discuss the factors that are responsible for the increase and saturation of thrust. The thrust gain was limited to approximately 2 at maximum because of the reaction force due to the backward plasma outflow and the prevention of thrust transfer by the shock wave, which caused the thrust to decrease when either the thermal or dynamic pressure was superabundant. The influence of the characteristics of the injected plasma on the thrust gain was evaluated in terms of density, temperature and radial outward injection velocity. In this study, we focused on magneto-sonic waves propagating in a direction perpendicular to the magnetic field lines. We assumed that this magnetic sound wave creates a shock wave in the magnetosphere. The magneto-sonic Mach number depends on the local plasma density and plasma velocity, however the influence of the density of injection is larger than the initial injection velocity among the parameters at the time of injection. It is shown that a magnetospheric structure with large thrust can be achieved if the injection plasma with a thermal pressure of about $\beta_{th}=2$ is given enough dynamic pressure to extend the ring current under low density and high velocity conditions. The density at which the thrust-increasing effect of the injection velocity can be obtained is restricted, with a low density at high injection plasma temperatures and a high density at low temperatures.

Chapter 6 shows the results of the calculations and estimates the propulsive performance, i.e., thrust, specific impulse, and power consumption, and spacecraft weight of an actual spacecraft, given the technical specifications of the present and near-future. The design was optimized for specific impulse in a spacecraft with a radius of 20 km and a coil weight of 210 tons. A thrust of 237 N was estimated with a power consumption of 87 MW. In this case, the annual fuel consumption is about 2000 kg. The MPS can achieve a specific impulse of 400000 s. In addition, the conditions under which the thrust performance can be improved by plasma injection are presented.

Chapter 7 shows the discussion. The magnetospheric structure and the optimal setting of plasma injection conditions for the MPS to produce high propulsive performance are presented. Furthermore, the MPS design has an impressive thrust-to-weight ratio, making it more suitable for round-trip transport missions between the Earth and Asteroid belts. At this time, the spacecraft thrust was estimated to be 210 N, the power consumption 24 MW, and the weight of the MPS propulsion system, including the power supply system, was re-estimated to be 260 tons. In this case, the spacecraft is estimated to have a thrust of 210 N, a specific impulse of 300000 s, a power consumption of 24 MW, and a weight of 260 tons for the MPS propulsion system including the power supply system. The MPS spacecraft can arrive at the asteroid belt from the near-Earth region in 0.7 years. After loading 1,000 tons of mining metal resources in the asteroid belt, the MPS spacecraft was able to return to the near-Earth region in 3.8 years.

This is concluding remarks. In the MPS analysis based on the MHD calculations, when magnetospheric inflation by plasma injection is performed at certain coil parameters, the coil magnetic field is a dipole field, and its poles are parallel to the solar wind, a mechanism was confirmed in which dynamic pressure promotes the development of ring currents and contributes to the increase in thrust. On the other hand, the thrust saturates when either the thermal or dynamic pressure is superabundant, the thrust gain never exceeds 2.3, in the parameter survey conducted in this study. This is due to the backward outflow of plasma in the magnetosphere and the obstruction of solar wind momentum transfer due to shock waves in the magnetosphere. And the mechanism of thrust increase was clarified, and the factor of thrust saturation was identified. Even under the same input energy conditions, the magnetospheric structure varies depending on the combination of thermal and dynamic pressure. To ease such thrust decrease effects, it was shown that the injection density should be reduced and plasma injection at high velocity should be performed. Such operation of the plasma source at low density and high injection velocity is also a condition that allows for high specific impulse of the MPS. The obtained thrust characteristics of the MPS are more beneficial than those of existing electric propulsion and magnetic sails in the Earth-asteroid round-trip transportation system. However, due to the thrust to weight ratio issue, it is necessary to reduce the power consumption of the MPS for this mission, even at the compromise of the specific impulse.

Form8・Separate Sheet
（様式８・別紙１）

Results of the doctoral thesis defense

博士論文審査結果

Name in Full
氏　　名　村山　裕輝

Title
論文題目　電磁流体解析による磁気プラズマセイルの推力拡大機構解明と磁気圏現象

地球を遠く離れた深宇宙を航行するための推進機としては、小惑星探査機「はやぶさ」のイオンエンジンが知られているが、より遠くの天体への大規模で効率的な宇宙航行を実現するためには、更に革新的な宇宙機推進の開発が不可欠である。本論文では、次世代型宇宙機推進の１つとして注目される「磁気セイル」「磁気プラズマセイル」に関する数値解析研究成果をまとめている。磁気セイルは、宇宙機周囲に人工的な磁気圏を生成しこれを帆（セイル）として太陽風プラズマを受け止めて推進する新しい宇宙機システムとして、Zubrin博士によって1990年に提案されたが、宇宙機を加速させるための推力特性が不十分であった。その後、人工的な磁気圏を拡大することで磁気セイルの推力増大をはかる「磁気プラズマセイル」が2000年にWinglee博士によって提案され、宇宙機を効率良く加速させる手段として注目を集めた。しかし、磁気プラズマセイルの推進原理については未解明な部分が多く、宇宙実証は未実施であり、実験室実験による推進原理実証も限定的である。出願者は「磁気プラズマセイル」の推力特性（推力ゲイン）が宇宙機から放出されるプラズマ放出条件に依存することに着目し、理想電磁流体(MHD)シミュレーションにより放出条件に関する広域サーベイを実施した。その上で「磁気プラズマセイル」の推力ゲインの上限値ならびに上限値の状態における電磁流体場を磁気音速マッハ数等の特性パラメータから説明することに成功した。「磁気プラズマセイル」の推力ゲインはこの臨界値で制約されるものの、磁気セイル（プラズマ放出を伴わない磁気セイル）に対して約2倍の推力を得ており、これら特性を基に磁気プラズマセイルによる宇宙機を提案している。

論文では、第1章にて磁気セイル・磁気プラズマセイル研究の現状と研究目的を述べた後、第2章および3章では、磁気プラズマセイルの基礎物理とスケーリング則を基に構築した数値モデルとその妥当性の検証結果が示されている。「磁気セイル」「磁気プラズマセイル」の研究としては2000年代以降に数多くの数値シミュレーション研究が実施されてきたが、解析精度と計算安定性の課題があり、「磁気プラズマセイル」からのプラズマ放出条件に関するサーベイが限定的で不完全であった。本研究ではプラズマ放出条件に関する広域サーベイを初めて実施し、「磁気プラズマセイル」による推力ゲインの上限値を確定させた点が新しい。計算モデルとして使用した理想電磁流体計算については、格子サイズへの依存性評価と実験室実験との比較とから検証され、推力特性を評価する上で必要な精度が得られていることを確認した。

本論文の第4章から5章では、数値解析結果が示されている。「磁気プラズマセイル」宇宙機から放出されるプラズマの条件としては、放出方向と放出プラズマ特性（温度・密

度・運動速度）を変化させ、推力特性が最適となる条件を探索するサーベイを実施した。なお、サーベイは、太陽風プラズマ流の方向と宇宙機に搭載するコイルの磁気モーメント方向とが一致する場合について実施された。「磁気プラズマセイル」推力値をプラズマ放出を行わない「磁気セイル」の場合と比較した「推力ゲイン」を比較したところ、プラズマ放出角度が磁気モーメント方向とほぼ直行する方向で推力ゲインが最大であった。また、放出されるプラズマ特性を示す無次元量としてβ_k値（プラズマ放出位置における動圧／磁気圧比）、ならびにβ_{th}値（プラズマ放出位置における静圧／磁気圧比）についてサーベイしたところ、最大推力ゲインは2.23となった。推力ゲインが2.2以上となる領域は、$\beta_{th}=2$、$\beta_k=4$付近に広く分布しており、この領域内では磁気圏内の宇宙機周囲流れ場も類似していた。β_{th}とβ_kを更に大きくした場合、この最大推力ゲインの流れ場に比較して、磁気圏内では放出されたプラズマ流が太陽風方向に流出・加速され、また、宇宙機周囲から宇宙機への波動伝搬が制約された。これらが原因で磁気プラズマセイル磁気圏が受ける力は磁気圏内プラズマ流にむしろ作用するため宇宙機に作用する力は増えず、これらが原因で推力ゲインの上限値が制約されることが確認された。

本論文の第6章から7章では、数値解析結果に基づいた宇宙機設計と関連した考察が示されている。数値解析では専ら無次元化した推力等特性値を評価したが、ここでは理想電磁流体モデルで評価可能な磁気プラズマセイルを提案している。提案された宇宙機は、重量600tから1,000tと現在の典型的な宇宙機に比べると100倍も大きく直ぐの実現は難しいが､大きなスケールと太陽風のエネルギーを利用した効率的な深宇宙航行が可能であり、磁気プラズマセイルが高い推進剤効率と大推力を両立可能な将来型宇宙推進コンセプトであることが明らかになった。

最後の第8章には、本論文の結論が記されている。

以上の成果は、磁気プラズマセイルの推力ゲインの上限値ならびに上限値の状態における電磁流体場を説明することに成功し、新規性と発展性があり、かつ、磁気プラズマセイルという次世代宇宙機コンセプトを支持する有益な結論が得られている。更に、本論文の主な部分は、査読付き学術雑誌2篇（筆頭著者）として掲載予定である。以上の結果を踏まえ、本論文は、博士論文として充分な学術水準に達していると判定した。