Magnetic Sail Propulsion

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ABSTRACT

A Magnetic Sail is a propulsion method utilized by spacecraft. It uses a static magnetic field to create momentum by deflecting surrounding charged particles. It is uniquely helpful in the propulsion of a spacecraft due to its capability to reduce the required thrust by a large factor. In this project we will be studying the electromagnetic processes implemented in its functionality. We will be focusing on its operation within a planetary magnetosphere.
INTRODUCTION

The concept of the magnetic sail was invented by Dana Andrews and Robert Zubrin, who collaboratively published a paper on the subject in 1988 [1]. Since then, many researchers and theoretical physicists have studied and made progress on this topic. It was expanded by Winglee in 2000 by introducing plasma injection as a means of expanding the magnetic field created[3]. Ikkoh Funaki, a member of the Japan Aerospace Exploration Agency and faculty of the Institute of Space and Astronautical Science, is a leading researcher in the aeronautic engineering field, in particular magnetic sails and propulsion systems that utilize magnetic fields [3]. He has 158 publications, with 43 conference papers and 114 articles related to the subject [3]. The majority of his work mainly focuses on the theoretical aspects of the magnetic sail and some small-scale experiments on its application. The design of the magnetic sail has steadily evolved over time, and the theoretical calculations performed have yielded very promising results, such as a thrust of 1 N at 4 kW, and an efficiency of 250 mN/kW, compared to a thrust of up to 200 mN and an efficiency of 20-30 mN/kW for an ion engine, what is currently used for some NASA space missions [2]. Recently, exciting progress has been made which may directly lead to the physical creation of the first magnetic sail.

THEORY

The goal of the magnetic sail is to catch the momentum of solar wind by making a gigantic magnetosphere around the spacecraft. Solar wind is defined as a continuous flow of charged particles, electromagnetic radiation, magnetic clouds and plasma from the sun that permeates the solar system [7]. The properties of this wind are not constant although it is always present. The propulsion is generated by using the interaction between the flowing plasma from solar wind and the automated magnetic field created outside of the spaceship. The energy from
the solar wind is transformed into the thrust of the magnetic sail, which results in a continuous, drag force radially from sun [3]. The thrust is proportional to the difference between the speed of the plasma flow and the velocity of the ship. If the ship is traveling faster than the solar wind, the sail can be used to slow the ship down. Because of the average speed of the plasma flow, a more likely use would be to accelerate ships towards their destination during interplanetary travel. Additionally, the density of the solar wind particles will decrease proportionally to the distance from the sun squared. There would then be less deflected particles as the distance from the sun decreased, and the thrust would be weaker. Deploying the magnetic sail may be cumbersome since it entails unreeling hundreds of kilometers of wire into a large circle. This process is not only time consuming but just impractical for modern spaceships. The magneto-plasma sail was proposed as a solution to this problem. In this design, a plasma cannon on board the ship injects plasma into the sail array while it is being deployed. This acts to expand the magnetic field farther with less coils necessary. A current is then induced into the boundary of the magnetosphere. Finally, the magnetic field interacts with the solar wind, and the resulting Lorentz force propels the ship forward.

**How it Works**

The magnetic sail has a simple yet unique design that allows it to accomplish its task efficiently and also reduce the amount of propellant needed to travel through space. The magnetic sail utilizes a large spool of superconducting wire, one hundred kilometers in diameter [1]. After deploying the wire into space behind the spacecraft, a current is run through the wire. This creates a magnetic field behind the spacecraft. Because of the properties of the superconducting wire, the current will remain indefinitely once initiated [1]. The newly created magnetic field will make the wire form into a rigid circular shape due to the hoop stress imparted
on the wire [1]. This helps the wire deploy properly and also helps keep its circular shape. Also, the superconducting loop is designed to operate at low magnetic fields, making it so there is no need to enhance the structure of the loop [1]. Usually, the magnitude of the magnetic field is in the magnitude of $10^{-5}$ Tesla [1]. The loop is deployed in such a way that the axis of the dipole is perpendicular to the flight direction [1]. The magnetic field of created deflects charged particles that enter it. This creates momentum that acts on the superconducting loop. The momentum would help the spacecraft propel itself, thus saving fuel. Figure 1 is an illustration of a magnetic sail.

![Figure 1 – Illustration of a magnetic sail [1]](image)

If the magnetic sail interacts with a plasma wind, such as a solar wind, the superconducting loop will accelerate the spacecraft in the direction of the wind [1]. This knowledge is the basis of the notion of faster space travel. It is known that the solar wind existing around Earth is a flux consisting of several million protons and electrons per cubic meter
at a velocity of 600 kilometers per second [2]. The solar wind around Earth could be utilized to accelerate the spacecraft up to the speed of the solar wind, which could cut the time to complete interplanetary missions significantly. For example, it is estimated that in implementing the magnetic sail in an interplanetary mission to Jupiter, the journey could be completed in 2 years, a feat currently impossible with modern technology [2]. The magnetic sail could also be implemented to significantly reduce the speed of the spacecraft for an interplanetary mission. The magnetic field would ionize the interstellar medium and also deflect the plasma surrounding the craft [1]. This would reduce the speed of the spacecraft significantly without using any propellant fuel in the process. Figure 2 is a diagram that shows the interaction of the solar wind on the magnetic sail.

Figure 2 – Diagram of the solar wind-magnetic sail interaction [1]
**Operation in a Planetary Magnetosphere**

The operation of the magnetic sail in a large exterior magnetic field has been considered and analyzed. The interference at distances from planets with magnetic fields would render the magnetic sail useless. The magnetic sail would be physically altered in shape if the magnetic field lines of the artificial magnetic field and the planetary field are not exactly parallel. The sail would still be useless even if not for this because the solar wind particles will have already been deflected by the planet’s magnetopause region.

In the magnetosheath and beyond, however, the magnetic sail has potential to be used for maneuvering capabilities and flight path adjustments if in orbit. This could be an important capability to have if the flight plan to an outer region in the solar system includes utilization of the gravitational slingshot effect around an intermediate planet on the way. Some simplified models of the magnetic sail deduce a maximum thrust/power ratio as $4 \text{ N/kW}$ [5]. With an estimated steering angle of up to $20^\circ$, large flight adjustments can be made if necessary due to a miscalculation, since no propellant is exhausted. This extra thrust will also be helpful to accelerate a spaceship after takeoff from the surface of a planet if marginal escape from the planet’s magnetosphere has been achieved.

**New Developments**

Since the late 1980’s, there have been numerous developments in this concept and technology. Ikkoh Funaki has been among the leaders in researching new materials for this propulsion technology. As recent as 2013, Funaki has designed conceptually a lightweight superconducting coil with size limitations for practical use aboard a satellite or spacecraft. The coil, a high temperature superconducting coil, or HTS coil, uses Yttrium Barium Copper Oxide (YBCO) coated conductors to realize the desired magnetic moment necessary for a magnetic sail
to work properly [5]. The coating compound exhibits high mechanical strength against electromagnetic forces, a critical criterion in designing such a device [5]. Due to the amount of hoop stress on the superconducting loop from the magnetic field, this compound was carefully chosen for its properties. Also, Funaki designed the coil to have limited size in order to fit on a smaller spacecraft, but also to have the highest magnetic moment possible with such a configuration, to the order of $10^7 \text{ A} \cdot \text{m}^2$ [5]. His work on the conceptual HTS coil may directly lead to the creation of the world’s first space propulsion system using a magnetic sail and HTS coil [5].
CONCLUSION

According to [5] magneto-plasma sail has a comparable force generated with respect to the amount of propellant used per unit time to the ion engine. It also achieves a higher thrust-to-power ratio than the ion engine and requires no extension mechanism like a solar sail. Its parameters are ideal for the outer planet exploration and it is adjusted or turned off by simply adjusting the current running through the sail wire. The magnetic sail propulsion system is continuously being theoretically improved, but it requires actual flight testing to be reliably evaluated since the magnetodynamic system is highly complex.
REFERENCES


