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博士論文の要旨

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論文題目

Electrical Phenomena Caused by Hypervelocity Impacts of Space Debris and Their Effects on Spacecraft

Space debris (referred to as debris) moving at an extremely high speed can collide with spacecraft. In this case, electrical phenomena, such as plasma generation, radiofrequency (RF) emission, and potential variation of the impacted target, can occur in addition to serious mechanical phenomena such as spacecraft destruction and secondary debris generation. Significant research effort has been focused on the mechanical phenomena to develop the shields against micrometeoroids or debris impacts. However, the research on electrical phenomena caused by hypervelocity impact has gained lesser attention than that on mechanical phenomena.

Herein, the plasma density and propagation of impact plasma were investigated to understand and estimate the risk of electric discharge on the spacecraft. Several plasma diagnosis methods exist; in particular, plasma probe methods can locally examine the plasma density by using multiple probes. Herein, the double probe method with a fixed bias voltage, which is one of the plasma probe methods, was used for this plasma measurements.

The spectroscopic method is a plasma temperature measurement method. Using this method, attempts have been made to measure the plasma temperature from the intensity ratio at three emission wavelengths from the luminous vapor cloud. However, if the line emission spectra derived from projectile and target materials are superposed on the wavelengths, the temperature cannot be measured. Moreover, the plasma density was calculated considering the ion mass of either the target or the projectile material, when impacts between the different target and projectile materials.

Hence, the study proposes a method to accurately calculate the plasma temperature using a spectroscopy via a streak camera. The streak camera spectroscopy can measure the time-resolved spectra in the wavelength range of 547 nm - 872 nm. The advantages of this method are that (1) the temperature can be calculated using the time-resolved spectra with a wide wavelength band and a large number of sampling points, and (2) the wavelength of the profiled emission line spectrum can be excluded from the temperature calculation.

Furthermore, the composition of ions, comprising impact plasma, has not been specified in the case of collision between different materials. By comparing the temporal change of emission lines derived from the target and projectile materials, it can be concluded that the impact plasma, comprising the target and projectile materials, is simultaneously generated. Therefore, a method can be proposed to accurately obtain the plasma temperature and density. The impact of spacecraft on solar cells and power harness systems can be accurately estimated by obtaining the precise parameters of the impact plasma.

Impact plasma induced by the hypervelocity impacts on solar cells can trigger electric discharge, which can cause a grounding fault in the spacecraft. Even though the power harness system behind the solar array paddle (SAP) and at the SAP boom is usually exposed to space, the electrical effects on the power harness system attributed to the hypervelocity impacts have received little attention. Previous studies have confirmed that grounding faults can occur because of the permanent sustained discharge (PSD) in debris collisions with a diameter of 0.2 mm or more. However, the frequency of these debris impacts on the power harness system of artificial satellites in a low Earth orbit simulated by a debris environment model is larger than the frequency of grounding faults in these satellites. Therefore, a deviation from the actual phenomenon is observed. Moreover, the effect of impact plasma on the power harness system is still unknown. Therefore, the PSD of the power harness system induced by the hypervelocity impacts is investigated herein.

In previous studies, the satellite load circuit was not simulated; thus, electric discharge can easily occur. Furthermore, multiple projectiles can simultaneously impact the power harness system because of the limitation of the impact test apparatus. When multiple projectiles impact, the impact plasma can interfere each other if the collision point is close. In this case, hypervelocity impact experiments must be conducted with single-particle impact to accurately evaluate the presence or absence of PSD occurrence.

Herein, experiments were conducted to re-verify the presence or absence of PSD occurrence by simulating a power harness system under conditions similar to those in the actual environment. In particular, the attention was focused on the circuit configuration and the multiple-particle impacts that can affect the occurrence of PSD. Two configurations cases with and without a load circuit were prepared and compared. Moreover, the array of double probes was set inside the measurement chamber to clarify the relationship between impact plasma and PSD.

Results indicated that the impact plasma can trigger the primary discharge and even a single-particle impact can easily result in PSD occurrence in the conventional configuration without a load circuit. The surface of the power harness system melted and carbonized near the impact points. However, a single impact does not result in PSD occurrence in the configuration with a load circuit with a resistance and a capacitance. Further, PSD never occurred even in the case of multiple-particle impacts. Therefore, the presence of a load circuit heavily affected the PSD occurrence by comparing previous studies. This result indicates that previous studies may have overestimated potential risks.

Regarding the microwave emission, it was confirmed that an RF signal with a wide frequency range of several kHz to several tens of GHz is emitted from hypervelocity impacts. RF emission arises from hypervelocity impacts on both metallic and non-metallic targets. However, the complete mechanism of microwave emission has not been investigated yet, although there are some suggestions that the microwave emission is caused by the impact plasma or by material destruction. To elucidate the mechanism of microwave emission, experiments were conducted by simultaneously measuring microwave emissions, impact plasma, and flash phenomena.

The microwave emission phenomenon can be clarified by simultaneously measuring the flash and impact plasma phenomena. The experimental results indicated that the time scale between impact plasma including light emission during dozens of microseconds and microwave phenomena during several milliseconds are significantly different.

Frequency characteristics investigation of the microwave emission was possible for the first time using the microwave measurement. In this measurement, two types of broadband log-periodic antennas were used. It was found that microwaves radiate in a wide band, but microwave emissions are shielded by high-dense impact plasma generated immediately after the impact. This suggests that the source of microwave emission is generated near the crater site inside the plume of the impact plasma.

Furthermore, to investigate the mechanism of microwave emission, hypervelocity experiments using various types of aluminum materials were conducted. The experimental results showed that the harder the target materials corresponded to a higher intensity of microwave emission. Using numerical simulations, it was found that the target hardness has a correlation with the elastic wave repeatedly propagating in the target material, and it is considered that the intermittent microwave radiation is related to the propagation of the elastic wave.

Conclusively, the electrical phenomena of impact plasma and microwave emissions induced by hypervelocity impacts were investigated. The accurate determination of the impact plasma parameters will enable the accurate estimation of discharge risk caused by hypervelocity impacts on solar cells and power harness systems mounted on the spacecraft. The proposed method to obtain plasma parameters can also contribute to the reliability of the satellite power system because of debris impacts by re-examining hypervelocity impact experiments on power harness systems. The microwave emission phenomenon is expected to be applied to estimate the scale, position, and frequency of debris collisions in the future. This work has contributed to both the basic and applied space engineering knowledge regarding electrical phenomena generated by hypervelocity impacts.

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（様式８・別紙）

Results of the doctoral thesis screening

博士論文審査結果

Name in Full
氏　　名　万戸　雄輝

Title
論文題目　Electrical Phenomena Caused by Hypervelocity Impacts of Space Debris and Their Effects on Spacecraft

本論文は,宇宙機のスペースデブリ（以降,デブリ）衝突で発生する電気的現象と宇宙機へ与える影響に関する研究成果の報告である。デブリは超高速で飛翔し,それによる衝突においては,クレータの形成や二次デブリの発生のような物理的破壊現象の他に,衝突プラズマやマイクロ波放射のような電気的現象が生じる。物理的破壊現象に関しては,主に宇宙機の防護バンパーの開発に関する研究が多くなされてきたが,電気的な現象に関する研究報告は少ない。本論文は,衝突プラズマやマイクロ波放射等の電気的現象に関して,二段式軽ガス銃を用いた室内実験と数値解析による取り組み,およびこれら現象の工学的応用を全 5 章構成で,英文で記述している。

第１章では,本研究の位置付けと研究目的が示されている。デブリによる宇宙環境の悪化が近年懸念されているが,デブリ観測技術の向上や大型デブリの除去技術などが検討されている一方で,出願者が対象とする小さなデブリは地上からの観測と追跡が不可能であり,また,大型デブリに比べはるかに数が多く,宇宙機と衝突する可能性が高い。出願者は,超高速衝突研究の重要性について示し,物理的破壊以外に,超高速衝突で生じる電気的現象に関して,知見が少なく,また,それらが宇宙機へ与える影響が明らかにできていないことを述べている。

第２章では,衝突プラズマのプラズマ密度を精確に求める研究について述べられている。短時間現象のプラズマパラメータの計測をダブルプローブ法と分光計測によるプラズマ温度計測との組み合わせで実現している。従来手法では,輝線スペクトルの影響により,分光法では正確なプラズマ温度推定が困難であった。出願者は,ストリークカメラ分光器を用いた新しいプラズマパラメータ計測手法を提案し,輝線スペクトルの影響を除去した正確なプラズマ温度推定を行った。また,輝線スペクトルを用い,異種材料衝突で発生する多成分プラズマの質量推定方法を提案した。新しいプラズマ温度計測と多成分プラズマのイオン質量推定により,正確な衝突プラズマ推定方法を実験的に示している。

第３章では,宇宙機の太陽電池パネルや電力ハーネスへのデブリによる超高速衝突に関して,衝突プラズマを介しての持続放電の発生と宇宙機の地絡故障が生じる可能性に関して,リスクの見直しが示されている。第２章で示された精度の高いプラズマ密度推定法を用い,電力ハーネスの超高速衝突による地絡故障リスクに関して,衛星負荷をモデル化し実験的検証が行われた。

第４章では,マイクロ波放射現象について述べている。出願者は,超高速衝突によるマイクロ波放射のメカニズムに密接に関係する現象と物性値を実験的に見いだした。光学観測やマイクロ波計測を可能にするため,衝突用真空チャンバーにアクリルを用いた衝突チャ

ンバを考案し,超高速衝突で生じる電磁波放射に関して,光の領域とマイクロ波領域の同時観測を行った。この同時観測により,マイクロ波放射が,衝突直後において,高密度の衝突プラズマにより遮蔽されていることを実験的に見いだした。これにより,マイクロ波の放射源は,衝突プラズマ雲を発生するクレーター近傍で発生していることを明らかにした。また,マイクロ波放射が硬度に関係することを実験的に見いだした。その実験的検証のために,異なる硬度の材料および組成が同じアルミニウム合金を調質違いで硬度を変えた材料を用いることで,マイクロ波放射に関する硬度に関連した新たな指標を示している。さらに,実験結果と数値解析結果の比較から,マイクロ波の断続的な放射には,超高速衝突によって標的材料内で繰り返し伝搬する弾性波の往来を示唆している。

第 5 章では,結論が述べられている。前章までの結果から正確なプラズマパラメータ推定に基づくデブリ衝突による放電リスク評価やマイクロ波を用いたデブリ衝突検知に関して衝突場所および衝突規模推定への応用への可能性など工学的応用についても言及している。

このように,本論文は,超高速衝突に関して,衝突プラズマの発生と伝播の定量的評価により宇宙機の放電リスクのより精確な評価手法の確立に貢献するとともに,超高速度衝突によるマイクロ波の発生源を特定できたことにより,マイクロ波放射を用いたデブリ衝突の検知技術への応用に貢献できたと言える。本論文は超高速衝突における衝突プラズマとマイクロ波発生現象に関する基礎的知見とさらに衝突プラズマが宇宙機へ与える影響の応用的知見の両方に貢献しており,宇宙工学分野での成果は顕著なものである。本論文の内容は,2 件審査制度の確立された学術雑誌へ投稿中であり,うち 1 件は文法に関するマイナーリビジョンの段階であり,十分に掲載にたる内容であることを確認した。

審査員は全員一致で、博士論文として充分な学術水準に達していると判断した。