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(Form 3)

Summary of Doctoral Thesis

Name in full CELIK Onur

Title Object-surface interaction in small-body surfaces

The recent observations from the small-body exploration missions have shown that asteroids and comets may have hard rocky surfaces and soft granular surfaces next to each other or mixed in the same region. This previously unknown variety in small-body surfaces poses challenges in understanding and modeling the interaction on natural and artificial objects with small-body surfaces, which is generally characterized by sub-m/s impacts. From an engineering perspective, the limited knowledge in the surface interaction makes it difficult to plan and execute spacecraft mission with surface operations. From more of a science perspective, it was recently observed that ejected particles from asteroid surfaces may reimpact and ricochet off the surface. To that end, the surface interaction of natural and manmade objects can be divided into two end-member cases as (1) hard non-penetrable surface and (2) soft granular surface. The models describing the former provides relatively simplified numerically tractable models. For the latter, on the other hand, the models are very varied and heavily relied on experiments (often material-specific) and discrete element method simulations. Even though the Earth-based studies are conducted to understand the interaction between natural and artificial objects with a variety of surfaces, the knowledge is still limited. This is primarily because of the unique environments found around small bodies, which primarily arise from their low-gravity, irregular shape, and surface environment. Creating asteroid environment on Earth is particularly challenging. For example, performing experiments on drop towers or parabolic flights are expensive and limited in accuracy and test cases. To overcome this, researchers often extrapolate Earth-based data or rely on simulations studies. While those have shown success on a theoretical level in building an understanding of the surface interaction on small bodies, they still lack a general theoretical framework or experimental validation. In this thesis, this gap is addressed by investigating two end-member cases of the object-surface interaction. The hard-surface interaction is investigated from an experimental perspective in artificial low-gravity while a theoretical framework is sought for interaction with granular surfaces. In each of these cases, the coefficient of restitution is given a central role. For the soft-surface case, a new analytical expression is derived via employing the long-established cratering theory. Dependencies of the coefficient of restitution to impact and surface parameters are investigated in both approaches. Finally, implications of object-surface interaction are investigated through a mission-design study.

In the first chapter of the thesis, a rigid body interacting with a hard surface is

investigated. The hard surface in this context refers to a type of surface where a rigid-body impactor (manmade or not) interacting with a surface without penetrating. Through this, the interaction between the two objects can be approximated as impulsive interaction. Because of that simplified approach, the hard-surface interaction model can offer a numerically-tractable solution by abstracting the interaction with a few coefficients characterizing surface. Thanks to its tractability, large Monte-Carlo-type simulations can be performed to understand overall trends in bouncing motion in small-body surfaces. However, despite their theoretical success, the model lacks an experimental validation under asteroid level gravity at low-speed impacts for nonspherical objects. It is of interest whether, for example, the coefficient of restitution is dependent on the object's impact velocity, impact angle, or impact attitude under asteroid-level conditions or how it can be characterized. Therefore, a set of impact experiments were performed with a cuboid lander assembly under two-dimensional artificial low-gravity created on an air-bearing table. Albeit being on two-dimensions, low-gravity created on an air-bearing table provides an inexpensive, easy, and more controllable environment than those of drop tower or parabolic flights. To that end, the experiments were aimed at representing impact velocities observed on asteroid surfaces thus far, with parametrically varied impact and attitude angle. The experimental results are used to investigate trends in post-impact motion and reveal dependencies of the coefficient of restitution to impact angle (in oblique impacts) and attitude angle (in normal impacts). The relationship to the impact angle is found to be more prominent and linearly increasing for the increasing angle. For the attitude-angle dependency, on the other hand, the relationship appears to be more complex, likely due to the rotational effects in post-impact motion. The relationship is found to be non-discernible at least for the impact velocities considered in the experiments. This study is one of the first examples of the hard-surface impact experiments for non-spherical impactors which is believed to be more representative of realistic lander shapes. The results provide realistic initial coefficient of restitution values for mission planning and trajectory reconstruction for small asteroid landers/hoppers, such as MASCOT or MINERVA-II onboard the Hayabusa2 mission.

The following part of the thesis investigates interaction with granular surfaces in asteroid-level gravity with analytical techniques. The characteristics of this type of interaction are that the surface is deformed plastically upon and after the impact occurs. The impactor is still assumed to be a rigid body. This type of interaction between an object and a granular surface has been studied in different perspectives from basic physics to planetary cratering. Most works are experimental or simulation-based and often material-specific due to the intrinsic complexity of granular materials. For the low-speed impact phenomena that characterize impacts of lander spacecraft or natural objects on small-body surfaces, the complexity is even higher, as granular behavior is

largely unknown in those environments. The currently-available experimental data of object-surface interaction in granular surfaces under low-gravity could only provide phenomenological explanations, while simulation studies are currently restricted to a few case studies. There is a general lack of analytical understanding that is supported by previous observations. To that end, the thesis study handles the object-surface interaction in the granular surface under low-gravity as a cratering phenomenon. The long-established cratering theory is investigated as a means to model object-surface interaction in granular portions of small-bodies for low-velocity impacts. Those crater-scaling laws have been successful in large craters arising from astronomical impacts, which occur at orbital speeds of several km/s in the past. Moreover, it has recently been demonstrated experimentally under Earth gravity that the theory can also capture small craters that occur as a result of low-speed impacts (~m/s). Building on this hypothesis, this research employs discrete-elements method simulations to prove the applicability of the cratering theory in low-speed impacts under low-gravity of small bodies. Then, the analytical expressions of the cratering theory are utilized to derive an analytical coefficient of restitution expression. As a result of the study, a critical impactor-to-target density ratio is identified for bouncing/submerging of an impactor. and an upper-limit coefficient of restitution value is estimated by the analytical model.

Implications of the object-surface interaction in a small-body surface are discussed in the context of the Deployable CAMera 5 (DCAM5) lander, an optional payload proposed to be deployed to the surface of Phobos during the Martian Moons eXploration (MMX) mission. In the DCAM5 case, the surface interaction becomes especially important as there are regions of Phobos that overflow its Roche lobe. A numerical study in the chaotic three-body problem showed that the escape speeds on Phobos can be as low as 2 m/s, contrary two-body problem estimation of ~9 m/s at minimum. Therefore, the maximum post-impact is restricted to a more realistic minimum of 4 m/s which could only be achieved via the surface interaction as DCAM5 has control capability. The results from the previous two chapters are applied to constrain the maximum impact speed with the chosen surface type. Through the estimated values in both hard and granular surface approaches, upper limits on impact speed and angle are determined to constrain the maximum post-impact speed to guarantee for surface settling. Combined with the deployment studies from MMX's planned quasi-satellite orbits (QSOs), the mission design space is constrained together with the surface interaction element. Reachable regions on the surface with this approach are discussed from the science point of view. The feasibility of the landing trajectories and the reachable regions are demonstrated to be strongly affected by the chosen surface type. While a granular surface allows for all access to the equatorial regions of Phobos, a hard surface restricts the landings to sub-Mars and anti-Mars regions only.

To conclude, the research presented here investigated the limit interaction cases in small-body surfaces from a multifaceted perspective through experiments, simulations, and analytical approaches. Implications of quantifying this interaction are demonstrated in a mission design example. The result found during this study could be used in more accurate operational planning on lander spacecraft and in understanding natural phenomena in small-body surfaces.

Form8・Separate Sheet
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Results of the doctoral thesis screening

博士論文審査結果

Name in Full
氏 名　CELIK Onur

Title
論文題目　Object-surface interaction in small-body surfaces

本論文は、物体と小天体表面の低速度衝突について、反発係数を主題とし、実験、シミュレーション、解析的手法を用いて多面的な視点から論じたものである。さらに得られた結果を適用しつつ具体的な小天体表面探査ミッション計画を検討することも行われ、本研究が独創的かつ有用なものあることが示されている。先行研究群に欠けていた点に着目し独創的なアイデアに従って研究が遂行され有益な結果が示されており、総合的に価値の高い論文である。

論文は全６章からなるが、核となるのは第３章および第４章であり、それぞれにおいて硬表面、軟表面における低速度衝突を扱っている。第５章は第３，４章で得られた結果を用いて火星の衛星であるフォボスに小型の観測装置を着陸させその表面を探査するという具体的な探査計画を検討したものである。

第１章では本論文の背景である小天体探査について過去および現在進行中のミッションが紹介され、とくに小天体を着陸する探査においては、低重力下の低速度（天体の脱出速度以下程度の速度：< ~m/s）衝突に対する表面応答特性が重要であることが明示される。小天体表面としては、低重力環境下における岩石のような硬い表面および粉体層のような柔表面が代表的なものであり、それらにおける反発特性を明らかにすることが重要として、それぞれのケースについて、これまで検討が不十分な点を掲げその解決方法とともに、本論文の構成・枠組みを提示している。第２章では、後続の議論の礎となるモデルについて紹介している。

第３章では、低重力を模擬したユニークな実験を行い、多様な条件下での非球形物体（直方体様物体）と硬表面の衝突特性を明らかにしている。これまでの研究では、低重力環境の実現にコストがかかることもあって、非球形物体の衝突といった多くの実験数（パラメータスタディ）が必要な実験が十分になされてこなかった。そこで本研究では落下塔のような大掛かりなものを要さずとも様々な重力環境を実現できる実験設備を構築し、衝突物の姿勢や衝突角度を変えながら何度も繰り返し実験を行った。その結果、衝突前後の運動傾向と反発係数について高精度の結果が得られ、さらに解析的な衝突モデルとも比較することで議論を深め、より確かな結果として提示している。

第４章では、数値シミュレーション(Discrete Element Method: DEM)により球状物体が軟表面（粉体層）に衝突した際に形成されるクレータの大きさや反発係数を求め、その結果を解析的手法により裏付けた。従来の粉体層衝突では実験にしろ数値シミュレーションにしろ数 100〜数 km/s といった高速の衝突について多くの研究がなされてきたが、本研究のターゲットとしている~m/s 以下の速度での衝突応答については不十分であった。

そこで本研究では、そのような低速度衝突の数値シミュレーションを数多く行いその衝突応答を明らかにした。とくに、低速度衝突であっても形成されるクレータの大きさは解析的手法で予測されるものと調和的でありスケーリング則が成立することが示唆され、反発係数について新しい解析式を導出している。

第５章では、前の２つの章の結果を組み合わせて、火星衛星の一つであるフォボスに投下し着陸探査する小型探査機の軌道条件についての検討を行っている。フォボスへの着陸探査を検討するうえでは、火星およびフォボスの重力を考慮しながら投下する軌道を解析する必要があるが、本研究では実際の形状モデルを用いたフォボス重力を再現し、着地軌道を求めている。モンテカルロ法を用いて得られた数多くの着地軌道に対し、表面状態を想定し前２章で得られた結果から推定される反発係数を仮定することで、許容される軌道を求めて提示するものとなっている。

第６章では、結果をまとめ、本研究の意義と今後の方向性が示されている。

このように、本論文では、基礎となる衝突の素過程を丹念に調べることを基本として、それを実際の小天体探査計画にまで応用するという流れを示したものである。独創的な実験手法などを取り入れつつも、様々な観点から検討を加えており、信頼性の高い基礎的データが得られていると言えよう。近年、小惑星探査は単なるフライバイにとどまらず、着陸探査・サンプルリターン探査が主流となりつつある。ここで示された結果と応用手法については、今後の小天体探査に十分に生かされるものと期待される。

以上、申請された論文は独自性・有用性を併せ持ち、博士論文としてふさわしいものであると判定した。