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(別紙様式 2)
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論文内容の要旨
Summary of thesis contents

軟弱地盤におけるテラメカニクスに基づく車輪型ローバの走行性能向上に関する研究
Study on Development Locomotion Performance based on Terramechanics for Wheeled Rover on Soft Ground

Many space missions are being undertaken to improve our understanding of the solar system and how to use space resources. The space exploration has possibilities that improve human life and inspires our curiosity.

There are various exploration methods such as fly-by, orbiter, sensor probe, lander, rover and sample return. The method of exploration is determined by interests of researchers and difficulties of explorations.

These days, the method of exploration is changing from the spotting type of explorations by fly-by and orbiter to the seeking type of explorations. The exploration of planetary surface by rover is focused on, because a rover is able to explore surface directly. It has opportunities to analyze rocks and soil, and to collect samples for bringing to the earth.

There have been many planetary rovers for the surface explorations, such as Sojourner and two Mars Exploration Rovers(MER), Spirit and Opportunity, operated by NASA, and Lunokhod 1 and 2 operated by former Soviet Union. Sojourner moved a total of about 100 meters around the landing area in 1997. Opportunity has traveled tens of kilometers in total on Mars up until now since 2004. Lunokhod 1 and 2 traveled tens of kilometers in total on lunar terrain in the 1970's. The exploration by rovers has enabled the scientific observations in the different terrain such as craters and hills.

When rovers travel on rough terrains, it is necessary to consider an interaction between a locomotion system and soils. Because the locomotion system easily slips and gets stuck on soft grounds and soft slopes. For developing the locomotion system to have a high mobility, many researchers have studied various locomotion systems such as a wheel mechanism, a track mechanism, a leg mechanism, and a leg-wheel mechanism. Wheel mechanism is lower traction and lower mobility on rough terrain, but multi-wheel improves traction ability and wheel with suspension improves mobility on rough terrain. Tracked mechanism has the best traction but it is said that it is vulnerable to dust and debris between the wheels and track. Advantage of leg mechanism is that it is able to move on a rough terrain better than other locomotion systems. Leg-wheel mechanism has the merit of both wheel and leg. However these locomotion systems have structurally complex and drawback of leg and leg-wheel mechanism is the complication control system. In many cases, the researchers have employed the wheel mechanism on the locomotion system of rovers. Because the

wheel mechanism is easy to mount the rover and control. It is also a simple structure.

However, a wheel easily slips. When a wheel slip increases, a traction force decreases. And then the wheel gets a stuck. Because the planetary surfaces are covered with soft soil called regolith. Actually both Spirit and Opportunity's wheels have got stuck on soft soil. Opportunity successfully recovered by accelerating in the top gear in June 2006. Spirit gave up traveling in January 2010 and then it made scientific observations at the same point where it got stuck.

The decrease in wheel slip makes rovers travel efficiently, and it will make rovers achieve traveling to different areas. Many researchers have been investigating methods of a decrease in the wheel slip on soft soils. For preventing an increase in the wheel slip and a stuck, researchers have studied various approaches considering an interaction between the wheel and soils, called terramechanics.

In terramechanics, two kinds of stress model are formulated by experiments. A normal stress model is formulated from a relationship between a contact pressure and a sinkage by penetration tests. Also a shear stress model is formulated from a relationship between the shear stress and a shear displacement by soil shear tests. These empirical models of the normal stress and the shear stress are applied to a wheel surface in soils. And wheel forces and a torque are formulated using a relationship between the normal and the shear stresses on the wheel surface.

The dynamic wheel sinkage should be considered in order to achieve the decrease of wheel slip by wheel control. It is not enough that the static wheel sinkage is only considered. Because the slip ratio changes during the increase of the wheel sinkage after the wheel starts rotating. The wheel force and torque during the wheel sinkage are determined by considering the dynamic wheel sinkage, and the increased amount of sinkage and amount of the slip ratio change are determined. Thus author can predict the change of wheel state from the transient state to static state.

However, the terramechanics-based wheel model (a conventional wheel model) does not treat the process of the wheel sinking. Because the conventional wheel model only considers a static state of the wheel sinkage, and is not applicable a calculation of the wheel forces and the torque in the process of the wheel sinking. Thus when author uses the conventional wheel model in dynamic simulations, the wheel sinkage oscillates after the wheel starts rotating. Also a wheel slip ratio reaches the same value of the slip ratio in the static state regardless of a wheel angular acceleration.

In this paper, author proposes a wheel model that considers the process of the sinking in order to suppress the increase in the slip. Author formulates the wheel model to solve the problems of the wheel sinkage and the slip. At first author proposes a dynamic normal stress model considering a wheel sinking velocity in order to solve an oscillation of the wheel sinkage. The proposed dynamic normal stress model does not treat the wheel slip in the static state. Thus author proposes a shear deformation model considering a variation of a shear characteristic in order to solve the problem of the wheel slip. Then author evaluates an effectively of the proposed model by simulations. In simulations, the input is constant wheel velocity, and the soil parameters of lunar regolith simulant and dry sand are utilized. The wheel force and torque are calculated using a slip ratio and a wheel sinkage via terramechanics-based wheel model. The forces and torque are used to update the wheel velocity and the wheel sinkage for the subsequent time step, and the wheel velocity is used to update the slip ratio.

Author also performs a single wheel experiments by understanding characteristic of wheel sinkage and slip when author inputs different wheel angular acceleration. Then author evaluates a practicality of the proposed model. At first, author performs a shear test to understand a parameter of the shear deformation modulus, and then author compares experiments results and simulation results that are used the proposed models and conventional model.

This paper is organized as follows. Section 2 describes the wheel dynamics model considering a wheel sinkage motion. Author focuses on a single rigid driving wheel in the process from a start to a finish of the wheel sinking. Also author defines the wheel model based on terramechanics. Section 3 describes a proposal of a wheel model that solves the problem of the wheel sinkage. At first author shows a simulation result using the conventional wheel model and point the problem of the wheel sinkage. Then author proposes the dynamic normal stress model that considers the wheel sinking velocity and a state variation of soils. Section 4 describes a proposal of the wheel model that solves the problem of the wheel slip. Author proposes the shear deformation model that considers a variation of the shear characteristic. And author evaluates the proposed models by simulations whether the proposed models are appropriate. Moreover, author performs the shear test to understand the parameter of the shear deformation modulus. Section 5 describes a single wheel experiments. Author understands characteristic of wheel sinkage and slip by inputting different wheel angular acceleration, and evaluates practicality of the proposed models by comparing experimental results and simulation results.

(Separate Form 3)

博士論文の審査結果の要旨

Summary of the results of the doctoral thesis screening

軟弱地盤におけるテラメカニクスに基づく車輪型ローバの走行性能向上に関する研究

審査委員会は，本申請論文が博士学位論文としての価値があると結論を出した．

本論文は，剛体車輪と軟弱地盤の間の相互作用を扱うテラメカニクスの一分野に関する研究である．テラメカニクスは，土壌と機械の間の力学を扱う研究分野であり，この分野の研究を進めることで，月面や火星表面など重力の大きな天体上を走行する車輪型　クローラ型ローバの挙動を力学的に解明することが期待されている．

従来のテラメカニクスモデルでは，静的な力の伝達しか考慮されていない．このため，車輪の動的な振る舞い，特に，車輪が沈下していく現象を扱うことができなかった．

本論文では，車輪と軟弱地面の間の力の伝達モデルに関して，以下の 2 点を考慮した動的な新しいモデルを世界で初めて提案している．

(a) 車輪が土壌に沈下する速度と車両が土壌をせん断する速度を考慮した力を，修正項として従来モデルに加えることにより，新しい力伝達モデルを提案した．

(b) 従来モデル中にも出現する砂の\せん断変形係数" を車輪の状態変数に依存する変数として扱うことにした．これまでのモデルでは，砂のせん断変形係数を一定定数として扱っている．

提案した新モデルの有効性は，数値シミュレーションと実験により検証している．

前者の新しい力伝達モデルに関しては，数値シミュレーションを行なっている．従来のモデルをそのまま使った動的シミュレーションでは沈下量が振動することを回避できない．しかし，新モデルでは，沈下量が漸近的に収束し，現実の車輪の振る舞いを再現することに成功している．

後者のせん断変形係数の変数化に関しては，まず，実際に砂のせん断試験を行ない，せん断する加速度を変化させることにより変数として扱えることを示している．

さらに，単車輪を用いた走行試験を実施し，車輪が停止状態から一定走行に至るまでのスリップ率，沈下量の変化を，数値シミュレーションと実験結果の間で比較している．新モデルによるシミュレーションでは，車輪が加速していく過渡状態において，スリップ率が沈下状態と共に変化し，加速方法によって最終的な沈下量が異なることを再現している．従来モデルにおいては，スリップ率は常に一定であり，過渡状態に関わらず最終的な沈下量は一定になり，現実の走行状態を模擬できていなかった．

この動的モデルは，車輪の制御系やオブザーバに組み込むことで，リアルタイムに車輪の状態推定を行ないながら最適な走行制御を行なうことを可能とする．つまり，惑星探査ローバの不整地走行に関して，スリップ率増大による車輪スタックの回避を行なうなど，制御系による走行性能の向上が期待できる．

このように，車輪と土壌との間の相互作用を直接，車輪制御に適用する道を拓いたということで，本論文は非常に意義の高いものである．