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Study on down-cutting ladder trencher of an underwater construction robot for seabed application

Mai The Vu [a], Sang-Ki Jeong [b,*], Hyeung-Sik Choi [b], Ji-Youn Oh [b], Dae-Hyung Ji [b]

[a] Department of Convergence Study on The Ocean Science and Technology, School of Ocean Science and Technology, Korea Maritime and Ocean University, 727 Taejong-ro, Yeongdo-gu, Busan, 49112, South Korea

[b] Division of Mechanical Engineering, Korea Maritime and Ocean University, 727 Taejong-ro, Yeongdo-gu, Busan, 49112, South Korea

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ABSTRACT

This paper presents the basic physics required to predict the performance of a down-cutting operation of a complete mechanical system including underwater tracked vehicle (UTV) and ladder trencher (LT) in a subsea application. The bar forces on a complete LT are assessed, by considering the forces generated by individual cutting tools when they are mounted on an LT. The thrust or traction requirements for the overall system (UTV and LT) are then estimated, and the required tractive thrust and normal reaction forces of the overall system can be calculated. In order to analyze the weight and balance requirements of the UTV, the moment of the LT caused by the cutting system is studied. The energy and power needed to drive the LT are then estimated and considered in relation to the tool characteristics. To demonstrate the application of various equations to practical problems of machine design or performance analysis, a number of numerical simulations are performed using the derived approach. This simulation provides important insight into the behavior of the trenching machine that can be used to design a trenching machine for the required working conditions. For this, the parameter study and sensitivity analysis are conducted to determine the variations of the operational and geometric parameters, and to observe how the cutter tools and material condition affect the forces, moment, weight, and power components.

1. Introduction

Occasionally, seafloor cables are laid across busy shipping routes and fishing areas where the seafloor is frequently disturbed by dredging, trawling, and anchoring. The seafloor cables can become damaged when exposed on the seafloor surface, and therefore need proper protection. To reduce the risk of damaging cables, effective cable protection and the careful execution of cable laying and burial operations are required. A seafloor tracked trencher equipped with jetting or cutting systems is used to bury submarine pipelines or cables. Numerous difficulties arise in attempting a strict scientific approach to the design of the complete UTV with an LT. Relevant theoretical soil mechanics is likely to involve controversial fracture theories and failure criteria, and to necessitate detailed material properties that are not normally available to a machine designer. Direct experiments are costly and time-consuming, and experimental data collected from the literature may be unsuitable for extrapolation, especially when they are described by relationships that violate the basic physics of the problem. Comprehensive mechanical analyses for soil-cutting machines have not yet been developed, and while established design principles for metal-cutting machine tools may be helpful, they do not cover all pertinent aspects. For example, significant differences are usually found in the forces and power levels between machine tools and excavating machines, while a force component that can be almost ignored in a relatively rigid machine tool could be a crucial design factor for large mobile rock cutters. Thus, understanding trencher interaction through analyses of the design and mechanics of the trencher is essential for autonomous operations of UTVs with a LT.

The seafloor tracked miner is a key subsystem of the entire deep ocean mining system. Tracked vehicles are preferred because of their better floatation and larger traction force, which are required for operation on the extremely weak deep-seabed soil. A number of studies have been carried out to investigate the performances of the tracked vehicles on the seafloor. Wong et al. [1] developed an analytical method for predicting the normal pressure distribution under a moving tracked vehicle, taking into account the response of

* Corresponding author at: Room 313, Building A1, Korea Maritime University, 727 Taejong-ro, Yeongdo-gu, Busan, 49112, South Korea.

E-mail addresses: maithevu90@gmail.com (M.T. Vu), koyoumy@hanmail.net (S.-K. Jeong), hchoi@kmou.ac.kr (H.-S. Choi).

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Table 1
Tracked Cable Burial Machines.

Type	Burial Systems Available	Maximum Burial Capability	Maximum depth of Operation	Operator
Eureka	Jet trenching system	1.0 m	1500 m	Global Marine
	Mechanical wheel cutter	1.2 m		
	Mechanical chain excavator	2.2 m		
Otter	Chain excavator for shallow water working	2.2 m	Within diver operations	Global Marine
Nereus III	Two separate burial tools available	1.0 m	2500 m	Tyco Submarine Systems Ltd
Atlas 1	Jet trenching system	Up to 1.0 m in sands and low to medium strength clays	2000 m	Global Marine
Excalibur	Jet trenching system	Up to 3.0 m in sands and low to medium strength clays	2000 m	Global Marine
CT 1	Jet trenching system	Up to 3.0 m in sands and low to medium strength clays	2500 m	CTC Marine Projects Ltd
Trencher T1	Jet trenching system	2.0 m	Up to 1000 m	CTC Marine Projects Ltd
	Mechanical chain excavator	1.2 m		
TM 02	Jet trenching system	1.0 m	Within diver operations	Travocean
	Mechanical wheel cutter	1.2 m		
	Mechanical chain excavator	2.0 m		
MED 1	Jet trenching system	1.0 m	120 m	Travocean
	Mechanical chain excavator	3.0 m		
LBT1	Jet trenching system	3.0 m	50 m	Marine Projects Int.
	Mechanical wheel cutter	1.2 m		
	Mechanical chain excavator	1.6 m		

the terrain to repetitive shear loading. Kitano and Kuma [2] developed an analytical method for investigation of the steerability of tracked vehicles in the time domain. They used the ground pressures under the road wheels to calculate the traction force of tracks in the form of Coulomb friction, assuming a planar vehicle motion. Baladi and Rohani [3] developed a stationary dynamic analysis method regarding the distribution of shear stresses along the tracks based on a more comprehensive soil model. Tran et al. [4] investigated the steering performance of a tracked vehicle operating over fresh concrete using stationary analysis.

LT machines are able to excavate in natural soil or rock using tools with screw clamps, and can operate in and out of water. Few studies have been published in the literature related to predicting the performance of LT machines. In-situ chain saw applications were analyzed by Mancini et al. [5] in terms of cutting performance, tool wear rate, and stone parameters. Primavori [6] investigated the operational conditions of chain saw machines in order to understand the effective use of these machines. Numerous analyses and design exercises have been undertaken. For example, Mellor [7] attempted to develop a systematic analytical scheme that can be used to facilitate future work on the mechanics of cutting and boring machines. Recently, Vu et al. [8] presented a study on the mechanics of the UTV system under the effects of an up-cutting mode LT working on the ground surface. Moreover, Vu et al. [9] conducted analyses on the design and mechanics of a developing underwater tracked vehicle with a rotating rock crushing too for rock excavation, working under the water.

Although many trenching machines have been manufactured by various companies around the world, information on methods to develop such machines is very limited due to the proprietary rights held by the companies. Moreover, the previous studies are limited since a method of implementing a dynamic analysis of the total deep ocean mining system is still lacking. Furthermore, no progress has been made in the understanding and modeling of cutter soil interaction, whereby the effects of force and moment have not been fully studied, and important factors are sometimes neglected since the dynamic interaction between the cutter tools and the soil mass is uncertain, complex, and difficult. In industrial sectors, many companies have gained considerable experience from designing and producing such machines during the gradual development and evolution of successive generations of the machines. For the rapid development of a trenching machine for specific operating conditions with certain performance characteristics requirements, an analytical yet practical approach is needed that can satisfy the requirements of all important features. Direct experiments are time-consuming and costly, and a strict scientific approach based on first principles such as theoretical soil mechanics has numerous problems such as the difficulty in finding detailed measured material properties, failure criteria, and selecting the fracture theories that should be used. Regarding these considerations, in this paper, a modeling method for the LT and further analysis of the interaction effects of the underwater LT on the UTV is analyzed.

The proposed trencher machine is compact and versatile and with the combination of various trenching tools such as ladder trencher tool/wheels-rock crusher tool, excavation under difficult conditions is made possible without compromising the safety of the cable system. Different tooling options are a new feature of this vehicle to enable burial to increased burial depth requirements. Equipped with the cutting wheel trenching through rocky or extreme hardness soils is feasible, even in uneven territories. In this paper an analysis of the trenching machines that can operate appropriately under specific conditions with a certain performance requirement is conducted, and an effective approach that covers all of the requisite important features is developed. The main aim of this paper is the encompassing of the full mechanics in the force-relation equations regarding the moment between the trencher activation and the working of the UTV on the surface. This paper also shows the way that the analytical model is derived and implemented for the design and analysis of the machine through a consideration of all of the target specifications. Accordingly, parameter studies and a sensitivity analysis are conducted to show how the variations of the operational and geometric parameters, as well as the cutting tools and the material condition, affect the force, moment, weight, and power components. Especially, the typical design-process steps that are followed for a trencher machine are fully presented. Through this design process, three main mechanical-design parameters of the LT such as the length of the LT bar L, the nose radius of the LT bar R, and the height of the pivot point above the work surface h are determined. Furthermore, a number of simulations for which the derived approach was used to demonstrate the application of various equations to practical problems regarding the machine-design process or performance analyses were performed.