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Two-belt continuous line bucket system: Its concept design and fundamental bucket motion experiments

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ABSTRACT

In order to stabilize the trajectory of buckets traveling on the sea floor for mining mineral resources, this study proposes a novel method to mine these mineral resources with traveling buckets whose trajectories are straight and predictable with the use of two axially moving belts. A concept design of the two-belt continuous line bucket (TBCLB) system is first introduced and then an experiment is then conducted using a model to examine the motion of the buckets near the floor. The results obtained demonstrate that with the TBCLB system the trajectory of the buckets can be stabilized as expected, and that special attention should be paid to the stagnation of the bucket traveling that occurs depending on the attitude angle of the buckets at touchdown instants.

1. Introduction

Worldwide demand for mineral resources has been growing rapidly, and it will be more pronounced globally in the near future. This social trend makes us recognize the importance of having more than one source from which we can obtain a mineral resource that is indispensable for a specific industry as a raw material. We can select ourselves an import of the resource from a production area and/or an exploitation of the resource. From the engineering viewpoint it is necessary to establish a reliable technology for exploiting the resource. Most of the mineral resources consumed in relevant industries are currently supplied from land mining, and this resource supply is envisaged to be maintained for two or more decades [1].

We know that the mineral resources are available from the ocean as well as from the land. Previous ocean explorations (e.g., [2]) discovered mud that include plenty of rare earth elements distributed on the floor in the Pacific Ocean.

Thus far, some methods were proposed for collecting muds or nodules, including mineral resources, such as the hydro-dredge [3,4], and the continuous line bucket (CLB) [5]. In the hydro-dredge method, a self-propelling robot suctions the muds or nodules and transports them into a pipe in which the muds or nodules are forced to flow upwards. In the CLB, a long, circularly shaped cable moves axially between the ocean floor and the surface to convey buckets attached on the cable. The buckets consecutively touch down onto the floor, and then travel on the floor to scoop the mud or nodules. Numerous recent researches on ocean mining have focused on the hydro-dredge. Meanwhile, the CLB is scarcely studied nowadays primarily because of the unsatisfactory results obtained from some tests in the effort to validate it [5–7].

Considering that we have not yet established a definitive method for ocean mining, we should target our efforts of refining the CLB toward practical uses. The CLB can be driven solely by axially moving a circularly shaped slender structure. The simplicity of the driving mechanism is one of the advantages of this method compared to other methods. Certainly, a disadvantage of the CLB lies in the instability of the trajectories of the bucket traveling on the floor [7–9]. These previous papers show that in the traditional CLB, the configuration of grounding part of the circularly shaped cable changes temporally, and thus the trajectories of those buckets randomly fluctuate, making the bucket trajectory unpredictable. It demands us to create a new design that is able to move all of the buckets along prescribed trajectories. This study provides a solution to this issue. If we can succeed in building up a better method maintaining the simple driving mechanism mentioned above and overcoming this disadvantage, this will surely allow the ocean mining technology to mature for use in practical applications.

This study attempts to show that the instability of the bucket trajectory can be eliminated by applying two belts. In this paper we propose a concept design of a two-belt continuous line bucket

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(TBCLB) system, and demonstrate through experiments on motion of the bucket on the floor, that the bucket trajectory becomes straight, and that its inclination and the interval among the neighboring trajectories can be predicted using a simplified model. Through the experiment this paper will find technical problems in the proposed system and discuss them to obtain insights for refining this system.

2. Design of two-belt continuous line bucket system

2.1. Concept design

In the following sections, we respectively refer to the ascending and descending parts of the belts, including the buckets moving upwards and downwards as ascending and descending lines.

Prior to the experiment on the motion of the buckets, we generated a concept design of the TBCLB to render the use of the proposed system feasible in the actual sea, and built an experimental setup based on that concept design. Parameters specifying the designed TBCLB are listed in Table 1. The present design was intended for mining manganese nodules. This process entailed setting a target value for the production of manganese nodules per year, and the specification of a speed of axial motion of the belts, an interval between neighboring buckets, and a daily operating period. The prescription of these parameters allowed us to calculate the gross number of buckets, and the gross distance of traveling by those buckets, thereby estimating the weight of manganese nodules needed to be mined by a bucket during the operating period. This design achieved a 20% bucket volume filling with manganese nodules.

Past ocean explorations revealed that a large amount of the manganese nodules is distributed at depths of 4–6 km off the coast of Hawaii or in the Indian Ocean. The lengths of the ascending and descending lines need to be adequate to reach from the floor to the surface. In the present calculation for the estimation of tension values in the belts, the length is assumed to equal the water depth at the mining site.

Table 1
Concept design parameters for the two-belt continuous line bucket (TBCLB) system. Listed in parentheses are the parameters of the small-sized experiment.

Symbol	Definition	Value
B_B	Breadth of the bucket	1.00 m (0.04 m)
	Height of the bucket	1.00 m (0.04 m)
	Length of the bucket	3.00 m (0.12 m)
C_d	Fluid drag coefficient of the bucket	1.50
I_B	Interval of neighboring buckets	5.00 m (0.20 m)
N_A	Number of buckets in the ascending line	1000
N_D	Number of buckets in the descending line	1000
P	Power of motor for driving an axial motion	5.57×10^3 kW
S_B	Area of bottom surface of an empty bucket	$0.25\ m^2$
S_B^*	Area of bottom surface of a bucket containing nodules	$1.00\ m^2$ ($1.60 \times 10^{-3}\ m^2$)
T_A	Total load on the top end of ascending line	9.27×10^7 N
T_D	Total load on the top end of descending line	4.63×10^7 N
v	Axially moving speed	$1.20\ m\,s^{-1}$
W_B	Weight of an empty bucket	5.00×10^2 kg
W_B^*	Submerged weight of a bucket containing nodules	8.36×10^2 kg
ρ	Mass density of sea water	$1.00 \times 10^3\ kg\,m^{-3}$
	Daily operating time	8.00 h
	Mass density of manganese nodule	$2.30 \times 10^3\ kg\,m^{-3}$
	Total length of a belt	1.004×10^4 m
	Water depth at the mining site	5.00×10^3 m

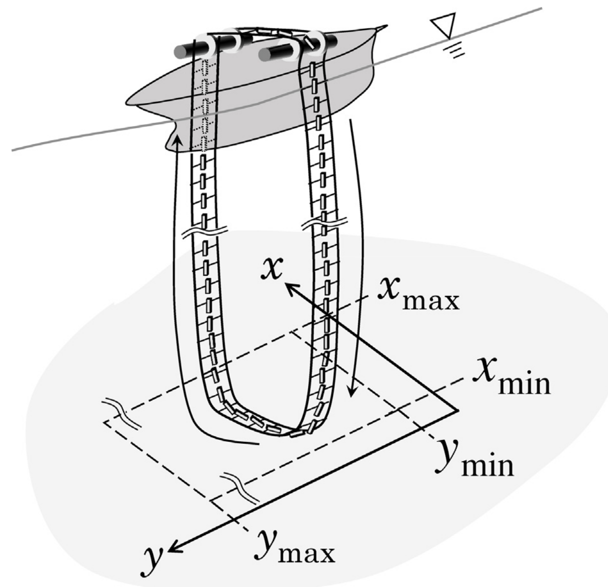

Fig. 1. A schematic illustration of the two-belt continuous line bucket (TBCLB) system. The x–y coordinate system representing a position in the mining region is drawn on the sea floor.

Table 2
Principal particulars of the mining ship designed in the concept design.

Symbol	Definition	Value
L_{pp}	Length of perpendiculars	130 m
B_{ext}	Extreme breadth	20 m
	Full-load displacement	13,000 ton
LW	Lightweight	7500 ton
	Maximum sea speed	31 knot
	Full load draft	7.0 m

In the TBCLB system, the roles of the mining ship include the towing of the belts to which the buckets are attached, and the support of the top ends of the ascending and descending lines (Fig. 1). Referring to the principal particulars of existing ships such as an auxiliary ship, we constructed a list of the principal particulars for the mining ship that is able to work in the TBCLB system. The full-load displacement and lightweight (LW) in Table 2 are set so that the ship is able to convey the manganese nodules that are brought and released by the ascending line, and that are subsequently stored on or beneath the ship during a mining operation.

The mining ship is equipped with a motor driving the axial motion of the belts. The power necessary for this driving is estimated as follows. The load on the top end of the ascending line is expressed as

$$T_A = W_A + D_A, \tag{1}$$

$$W_A \equiv W_B^* N_A, \tag{2}$$

$$D_A \equiv \left(\frac{1}{2}\rho C_d S_B v^2\right) N_A, \tag{3}$$

where W_A and D_A respectively denote the total weight of the ascending line and fluid drag acting in the direction opposite to the axial motion. Similarly, the load on the top end of the descending line is written in terms of the symbols W_D and D_D that respectively denote the total weight and fluid drag

$$T_D = W_D - D_D, \tag{4}$$

$$W_D \equiv W_B N_D, \tag{5}$$