Ocean Engineering 149 (2018) 170–182

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

On-board measurement methodology for the liquid-solid slurry production of deep-seabed mining

Jae-Won Oh [a], Jung-Yeul Jung [a,*], Sup Hong [b]

[a] Technology Center for Offshore Plant Industries, Korea Research Institute of Ships & Ocean Engineering (KRISO), #32, 1312 Beon-gil, Yuseong-daero, Yuseong-gu, Daejeon 34103, South Korea

[b] Ocean System Engineering Research Division, Korea Research Institute of Ships & Ocean Engineering (KRISO), #32, 1312 Beon-gil, Yuseong-daero, Yuseong-gu, Daejeon 34103, South Korea

ARTICLE INFO

Keywords:
On-board measurement methodology
Liquid-solid slurry
Deep-seabed lifting system
Recovery test of manganese nodule

ABSTRACT

The mineral resources in deep-seabed are attracting extensive attention because terrestrial natural resources have become progressively depleted. To optimize the mining system for the deep-seabed minerals, the production rate and the solid fraction of liquid-solid slurry production should be estimated and measured, precisely. However, there are very unstable on-board conditions due to the wave, tide, etc. In this research, we studied on on-board measurement methodology to estimate the production rate and the solid fraction of the deep-seabed mining. We proposed a measurement technique using the measured data and physical properties of materials. The technique has been verified by the real sea experiment using pilot-scale lifting system. Also we performed the Fast Fourier Transform (FFT) analysis because there are significant noises in the measured data. As a result of the FFT analysis, we found that the causes of the noises were due to the vessel behavior by the wave energy and the sloshing effect of the slurry in the storage tank.

1. Introduction

The importance of technology development to secure deep-sea mineral resources such as manganese nodules is being recognized globally, because the terrestrial natural resources have become progressively depleted. For this reason, many concepts of the commercial production for deep-sea mineral resources have been studied in advanced countries such as Germany, USA, and Canada from the 1970s (Padan, 1990; Li et al., 2013; Valsangkar, 2003; Sharma, 2011; Senanayake, 2011; Wijk et al., 2016). Since the 1990s, Korea has researched and developed technologies for the continuous production of deep-sea mineral resources. A deep-seabed integrated mining system (as shown in Fig. 1), which is composed of a mining robot and a lifting system (flexible pipe, buffer, and lifting pipe and pump), had derived as a system concept for production of deep-sea mineral resources in this R&D project (Oh et al., 2017). The mining robot collects the mineral resources on the deep-sea floor. The lifting system carries the mineral resources from mining robot to mining vessel. The development of this integrated mining system has been completed in 2016.

The developed mining robot is a self-propelled underwater robot to secure deep-seabed mineral resources. The flexible pipe is an equipment to transfer the mineral resources from the mining robot to the buffer. The buffer is a primary storage equipment to store the mineral resources delivered from the mining robot. The lifting pump and pipe carry continuously a certain amount of the mineral resources from the buffer to the mining vessel. The mining vessel has process facilities for refining and separation of the mineral resources transferred on-board.

These devices of the integrated mining system are operated in special and extreme conditions such as ocean environment and soft ground. For this reason, reasonable design and technology development of these devices are very important for stable operation of the system (Ertas and Yilmaz, 2014; Oh et al., 2016; Xiong et al., 2017). Korean researchers had used advanced engineering techniques such as simulation-based design method, uncertainty-based design method, and automatic control method for development of the reasonable integrated mining system (Choi et al., 2011; Lee et al., 2012; Oh et al., 2014, 2016; Yoon et al., 2014). The developed integrated mining system by the advanced engineering techniques should verify the system safety and reliability through real-sea experiment.

In 2012, 2013, the mining robot of the integrated mining system had been evaluated by real-sea experiment (Hong et al., 2013). This experiment evaluated resources harvesting ability and driving performance on

* Corresponding author.
E-mail address: jungjy73@kriso.re.kr (J.-Y. Jung).

https://doi.org/10.1016/j.oceaneng.2017.12.016
Received 25 August 2017; Received in revised form 29 September 2017; Accepted 6 December 2017

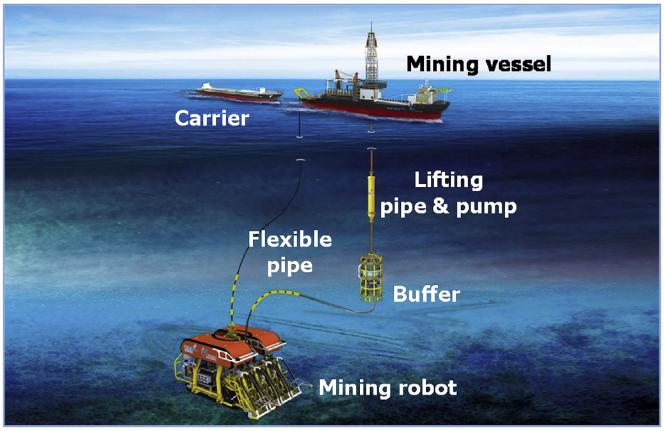

Fig. 1. Deep-seabed integrated mining system in Korea (Oh et al., 2017).

the sea floor of the mining robot. According to the experiment results, it was clarified that the mining robot had been well developed without any technical problems, and had the sufficient performance for commercialization. The results of this experiment were published in several papers (Hong et al., 2013; Yeu et al., 2013; Sung et al., 2014; Oh et al., 2017). After 2014, the lifting system shown in Fig. 2 and on-board facilities had been developed. Concept verification of the lifting system and the performance evaluation about continuous lifting had been analyzed and discussed by Hong et al. (2016) and Yeu et al. (2016). According to their results, the system had been operated without any technical problems.

The most important factor in the performance evaluation of this system is a predicting method of the total production of resources such as manganese nodules on board. In particular, a method to estimate the production of nodules contained in slurry is needed, because the nodules carried through this system become a slurry mixed with sea-water. So far, the slurry has been studied in various fields such as resources development field (Wu et al., 2015; Vedachalam et al., 2016; Khalil et al., 2017; Simone et al., 2017), simulation R&D field (Jakobs et al., 2012; Miedema, 2016), chemical and physical properties of slurry (Lu and Tassou, 2012; Merrill et al., 2017) and multiphase flow measurement system development (Falcone et al., 2009). However, there are few studies to develop the equipment for estimation of the production of the nodules as mineral resources contained in the slurry. Therefore, we proposed a measurement methodology of liquid-solid slurry to measure the content of nodules in the slurry. Furthermore, we developed a measurement system and applied it to the field test of lifting system to verify the methodology.

The proposed measurement methodology is a technique to estimate the total production by calculating the mass rate of nodules contained in the slurry through physical properties such as the density and weight that can be easily measured. This technique can be used as an on-board monitoring method to estimate the total production, because the distribution of the nodule in the slurry can be estimated by real-time measurement of the slurry transported on board.

However, precise measurement is difficult due to various factors such as a vessel behavior, mechanical vibrations and fluctuations of internal flow in pipeline. Measured data using the proposed measurement methodology also had measurement error due to various causes. For this reason, validation of the measurement methodology should be performed through error analysis of the measured data in order to verify the proposed measurement method. It is very important to find a way to improve the measurement accuracy by eliminating the cause of the error. Therefore, this paper introduces an on-board slurry measurement methodology and system for estimation of nodule production, and a feasibility study of the measurement methodology through application of the pilot-scale lifting test of manganese nodules was discussed in this paper.

2. Measurement methodology of liquid-solid slurry

The amount of nodules in the slurry should be measured to verify the capability of the lifting system for recovery of nodules. In this study, we applied the method to calculate the composition ratio of the mixture by measuring the physical properties such as weights, volumes and densities to measure the nodule content in the slurry.

The composition ratio of the mixture in the slurry can be calculated by comparing the density of the slurry and the densities of the sea-water and the nodule. The density of slurry is estimated by the weight of slurry. The relationship between the weight (W_s) and density (ρ_s) of the slurry is expressed as Eq. (1).

$$W_s = \rho_s g V_s \tag{1}$$

Fig. 2. Lifting system: buffer (left), lifting pump (middle) and lifting pipe (right) (Hong et al., 2016).