Sea Trial and Free-fall Hydrodynamic Research of a 7000-meter Lander

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***Abstract*—Hadal science is one of research frontiers in earth science. Exploring the hadal zone has become an attractive and challenging event in marine engineering due to extremely hostile environment. Only few underwater vehicles have the ability to dive deeper than 6000 meters. Free-fall vehicle, also known as "lander" has been widely applied in marine investigation for decades, and has made a spectacular achievement in hadal research. This paper presents the sea trial and corresponding results of a 7000-meter lander, which mainly focused on biology and ecology research in hadal zone. The sea trial was conducted in shallow water area and deep-sea area in South China Sea, where functional tests, descent/ascent speed characteristics, and comprehensive performance were studied. During the deep-sea trial, a serial of scientific research achievements was obtained. Sea trial results validated the multi-function, effectiveness and stability of the lander system.**

Keywords—free-fall vehicle; lander; sea trial; imaging; water sampling; funnel trap; deep-sea fauna; free-fall hydrodynamics

I. INTRODUCTION

The hadal zone, depth rating from 6000 to 11000 meters, is still one of the least known habitats on Earth [1]. Until the middle of last century, explorers and scientists taken some sporadic explorations to the extreme depth of oceans, and extraordinary characteristics of the hadal zone were gradually revealed, such as high hydrostatic pressure, heavy darkness, and low temperature, which intuitively make the habitat hostile for organisms to live. Nevertheless, hadal fauna were found to be rich in species diversity and abundance through trench explorations during the past few decades, which is distinctly inconsistent with the previous thought [2, 3]. Lacking of systematic and standardized sampling and investigating methods, our knowledge about the hadal zone is merely the tip of the iceberg.

Recent advances in marine engineering technology, such as the *'Kaiko 7000'* ROV [4], the *'Nereus'* Hybrid ROV (lost in May, 2014) [5], human occupied vehicles (HOV, the *DEEPSEA CHALLENGER* [6], the *JiaoLong* [7])，provide us opportunities to break the knowledge gap of hadal zone. Such advances are among the few underwater vehicles that could dive deeper than 6000 meters. Unlike these movable vehicles, free-fall bottom landers are unmanned and untethered stationary platforms, which perform tasks near the seafloor. Landers have been widely applied in benthic bottom explorations and research since the early of last century [8, 9], for their advantages in ease of use, low disturbance, little demanding of ship time, and capability of long-time implementation [10]. A spectacular progress in acknowledging the hadal community has been achieved by utilizing hadal landers in the "HADEEP" project, which developed by the University of Aberdeen (U.K.) cooperated with the University of Tokyo (Japan) [11]. During James Cameron's DEEPSEA CHALLENGER expedition in 2012 [12], landers are also applied to accomplish arranged tasks and successfully dived into the deepest place on earth: the Challenger Deep in the Mariana Trench.

Exploring in hadal zone becomes one of the most challenging and exciting events in marine engineering. Shenyang Institute of Automation, together with Sanya Institute of Deep-sea Science and Engineering, has planned to design a 7000-meter lander for hadal research, especially focused on biology and ecology research of hadal zone. The lander system overview is briefly introduced in section II. The lander was manufactured and functionally tested in water pool before August, 2014. In this paper, sea trial of the lander and corresponding results are presented. The sea trial was carried out in two stages: first one was performed in sublittoral zone last September, where pier tests and basic functional tests were conducted, details described in section III; the other was in bathyal zone, where comprehensive deep-sea tests of the whole lander system were conducted, as described in section IV. Free-fall hydrodynamics of the 7000-meter lander is demonstrated in section V, and in section VI conclusion is presented.

II. LANDER SYSTEM OVERVIEW

A. System Design

The 7000-meter depth rating lander shown in Fig. 1 was designed for hadal research, and can be divided into three parts, delivery subsystem, powering and control subsystem, and scientific payload subsystem. The delivery subsystem is composed of a main frame, a buoyance package, ballasts and other basic equipment. The powering and control subsystem consists of four components, i.e., two lithium batteries, a main controller, a power managing module, and a video

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recording/processing module. While the scientific payload subsystem contains an CTD, a digital stills camera, a flashgun, a video camera, two LED lights, a Niskin bottles, a sediment sampler and funnel traps. Here, it needs to be emphasized that the key component of the lander, a low power consumption mainboard is recommended, whose main function is system status monitoring, survey strategy managing, device power controlling, data acquiring and recording. More details about the design of the lander can be found in [13].

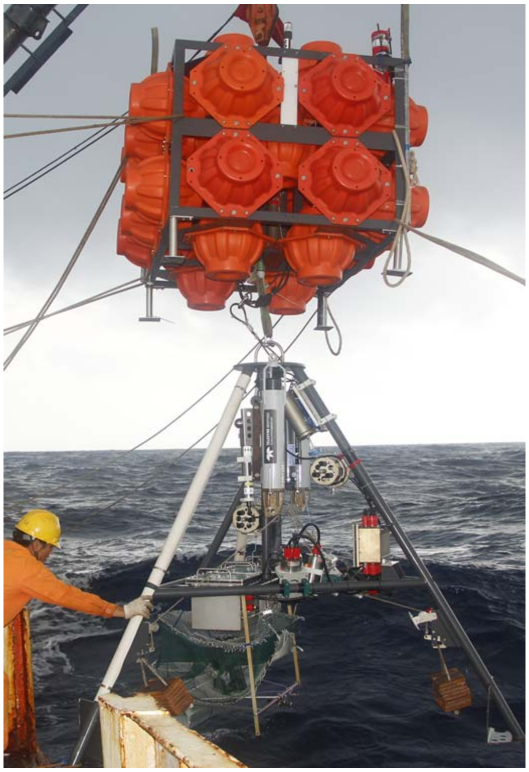

Fig. 1. The 7000-meter lander system.

B. Operating Procedure

The system operating procedure can be generally divided into seven stages: deck configuration stage, launching stage, descending stage, task performing stage, ascending stage, surfaced stage and recovery stage. Devices might work in different conditions to minimize power consumption and other system resource losses in different stages. Specific procedure is given as follows.

During deck configuration stage, some preliminary works can be done through Lander System User Interface running on a PC, such as, parameter settings, tasks planning, system initialization and functional test, while the PC is connected to the control subsystem through a cable. Once the configuration is settled, the cable will be removed, which means the lander system is disconnected with the mother ship. Then the lander system works in a self-control mode. Consequently, the critical issue of the controller is to decide which stage the lander system is in and then control each device to perform in corresponding conditions. State transition of the system mainly relies on measured values of the depth meter, altimeter and electronic compass.

III. Shallow Water Sea Trial

The lander system was tested in water pool from June to August, 2014 in Shenyang, and then transported to Sanya. The shallow water sea trial was carried out near Sanya during late September last year.

A 100 tons of displacement fishing boat equipped with a fixed portal-frame at the aft was rented as the mother ship during shallow water sea trial. Launching and recovery of the lander system was a little complicated, because the lander was still inside the boat even lifted by the winch. External force was needed to push the lander out of the aft. In order to practice system launching and recovery, several tests were conducted primarily at the pier in the first two days.

A. Functional Tests

1) Release Mechanism

Before comprehensive experiment, functional test of each module was conducted. Note that release mechanism is the key security assurance of the lander system, and was strictly tested. Three independent ballasts release approaches, that is, acoustic release, actively controlled release and timing release, were applied to improve the safety and reliability of the lander system.

Acoustic releasing was achieved by sending an acoustic command from a deck unit to the underwater acoustic release unit mounted on lander frame. In functional test stage, the acoustic release unit was disassembled from lander frame and tested separately. Success rate of the releasing tests was 100%. Nevertheless, due to the complex environment in shallow water near the pier, effective communication range, i.e., slant range from the transponder to the release unit, was extremely limited.

Actively controlled releasing would be triggered once a fault or an emergency is detected by the main controller, such as an abnormal descent speed, a depth beyond the pre-set threshold or reduction of the electrical insulation. To accomplish functional test of this release mechanism, a lower speed or a shallower depth threshold was intentionally set. By this means, effectiveness of the function was verified.

Timing release mechanism was recommended to release the ballasts in case of an unexpected error occurred to the acoustic release mechanism. It was considered as the final barrier to guaranteeing that the ballasts could always be released reliably. Thus the timing release mechanism were tested repeatedly, and the results indicated that timing release mechanism is highly reliable and stable.

2) Basic Equipment

Because basic equipment of the lander, including acoustic release, altimeter, pressure sensor, electronic compass, Iridium beacon, Xenon flasher, and hydraulic compensator, is essential to maintain normal operation of the system, they were all carefully tested before the sea trial except the Iridium beacon due to unavailable Iridium service. Considering that GPS positions of the lander could not be read from the mother ship, a safety rope was tied to the lander frame with the other end tied to the float sphere to label the lander's location.

3) Scientific Payload

The designed 7000-meter lander is focused on the biology and ecology research in hadal zone, thus equipped scientific payloads consist of a video camera, two LED lights, a high resolution still camera and supporting flash gun, an CTD profiler integrated with a dissolved oxygen sensor, a Niskin bottle, a sediment sampler and a funnel trap. Here, functions of video recording and digital stills photo capturing were particularly tested.

Video recording subsystem is composed of a full ocean depth and low power consumption CCD video camera, two oil-compensated LED lights, and a special video recording/processing module. The video recording subsystem works in a distributed control mode, that is, the subsystem accomplishes video recording and image processing independently, meanwhile under the control of the main controller through serials communication. Once the video camera was powered on, the video recording/processing program would run automatically, analyzing image sequences to detect moving objects while recording video data until receiving a shutdown command from the main controller. However, the program was not completely finished before the sea trial, and needed to be booted manually. Checking the video quality in underwater environment is also one of the test contents. According to the original design, two LED lights were arranged in parallel with the video camera. In this case, intensely reflected light from suspended particles in sea water was very strong, resulting in bad video quality. Rearranging illuminating angle of the LED lights after several attempts, video quality was improved significantly.

High resolution photos were taken by a digital stills camera supported with a flashgun. The shooting could be triggered by the main controller in two ways, fixed timing trigger and motion detected trigger, but only the former was adopted in this sea trial, since motion detected program had not been finished then. Essential settings of the camera were adjusted to adapt the underwater environment.

A Niskin bottle was modified so that it could be triggered passively with ballasts releasing, through which bottom seawater sample could be collected. Sediment sampler and fauna trap were also tested.

B. *Descent and Ascent Speed Tests*

Another important test was to study the free-fall hydrodynamics of the lander. Vitrovex® glass spheres and standard 5-kilogram iron blocks were used to provide positive buoyance and negative buoyance respectively. The number of glass spheres was a constant value of 28, while the quantity of iron blocks was variable to generate different buoyance conditions.

The tests were conducted by calculating descent and ascent speed in different ballast conditions. Detailed results would be given in section V.

IV. Deep-sea Trial

Deep-sea trial of the 7000-meter lander system was subsequently performed in last November. Functional enhancements and stability improvements were made based on the application experience of the shallow water sea trial, details showed as below.

A. *Appended Function*

1) *Water Sampling at Specified Depth*

As mentioned above, a Niskin bottle was equipped to collect bottom water sample. However, collecting water sample from the same location at different depths makes sense for scientific research. For this purpose, another Niskin bottle was vertically mounted on the lander frame, with both end caps tied to the actuator of the active releasing mechanism, which meant water sampling could be triggered by the main controller, shown in Fig. 2. Considering that the active releasing mechanism would not be triggered unless an emergency occurred, the end caps of the vertical Niskin bottle would keep open under normal circumstance. In case that collecting water sample at specified depth affected other functions especially ballasts releasing function, water sampling was triggered during the ascending stage.

Fig. 2. Niskin bottle equipped for bottom water sampling (left) and for specified depth water sampling (right).

2) *In-situ Microorganisms Enriching and Fixation*

Engineer Jun Li from Sanya Institute of Deep-sea Science and Engineering, CAS, also a member of our research team, was developing a device for in-situ microorganisms enriching and fixation at that time. It happens to be finished before the deep-sea trial, so the device was equipped on the lander system to acquire microorganisms fixed in-situ, as shown in Fig. 3.

Fig. 3. In-situ microorganisms enriching and fixation device.

B. Landing Site Positioning

The lander would drift out of its launching position by a variety of factors during its descent [10], which resulted in an uncertain displacement between the landing site and launching position. So first, it is necessary to know location of the landing site where samples were taken. Ultra-short baseline (USBL) positioning system is a common approach to achieve underwater objects positioning [14], but extra costs and higher requirements for the mother ship will be needed. In this sea trial, a practical positioning method, which is usually used to locate bottom beacons, is recommended to locate the landing site.

The basic theory of the positioning method can be presented as

$$(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2 = d_i^2 \tag{1}$$

where (x_i, y_i, z_i) is GPS locations of the mother ship, (x, y, z) is the coordinates of the lander and di is the slant range between the mother ship and the lander, obtained by communication from related deck unit to acoustic release. All the coordinates are described in the inertial frame established at any point on the surface.

At least three locations of the mother ship are needed to calculate the coordinates of the lander, and the accuracy relies on the range of measured points of the mother ship, underwater communication environment, surface current, and etc.

C. Deep-sea Trial Summary

Five deep-sea deployments were conducted in three stations during the trial, reaching a record depth of 2856 meters. The lander system worked about 39 hours on the seafloor in total, recording 24.5 hours' video data and thousands of high resolution photos. The CTD profiler was powered on after the system launched to measure conductivity, temperature, pressure, and amount of dissolved oxygen in the vertical section. The system performed normally as desired except for the third deployment in which an unexpected program fault occurred, resulting in system crashing a moment after deck launching, and no data recorded.

The adopted Iridium beacon started to work before the sea trial, which meant safety rope was no more required in deep-sea trial. There was a short delay of approximately 10 minutes from the lander system surfaced to the Iridium phone received the message, which was acceptable for lander system recovery.

Desired depth of water sampling can be specified through the Lander System User Interface during the deck configuration stage. Proposed water sampling method was proved to be effective. In-situ microorganisms enriching and fixation device was applied in last two deep-sea trials, during which 0.72L and 8.4L seawater were filtered respectively.

D. Scientific Research Achievement

During five deployments, a series of scientific research achievements were made. Seven *Bathynomus giganteus* were captured in the third deployment, shown in Fig. 4. The digital stills camera and video camera succeeded in recording high resolution photos and motion movies of the deep-sea fauna, as shown in Fig. 5.

Fig. 4. *Bathynomus giganteus* captured by funnel trap.

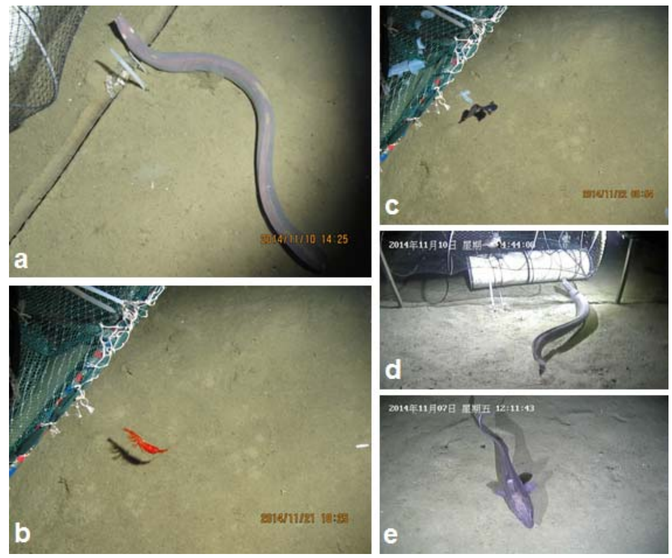

Fig. 5. Photos taken by still camera(a~c) and screenshots of video record(d,e).

Conductivity, temperature, pressure, and amount of dissolved oxygen were measured in five stations, not only in vertical plane but also near the seafloor. Eight bottles of seawater samples were collected in total, of which three were sampled in specified depths. Several bacterial colonies were isolated from the in-situ fixed microorganism samples.

V. Results of Free-fall Hydrodynamics

Requirements for the descent and ascent speed are variable corresponding to different purposes, for instance, low speed is needed to reduce environment disturbance, while high landing speed would be better for sediment sampling. Hydrodynamics study of the lander system was carried out both in shallow water sea trial and deep-sea trial.

During shallow water sea trial, descent and ascent speed in different ballast conditions were measured, and related results were shown in Fig. 6. Because the ambient density and pressure, which are two crucial factors for system buoyance, change with depth, buoyance of the lander can no longer be regarded as a constant in deep-sea. Fig. 7 shows the descent/ascent speed variations with respect to depth.

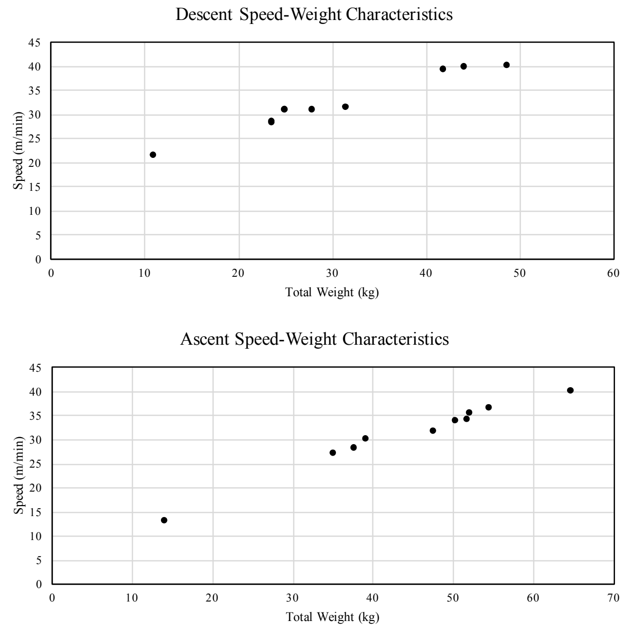

Fig. 6. Descent/ascent speed varying with total weight.

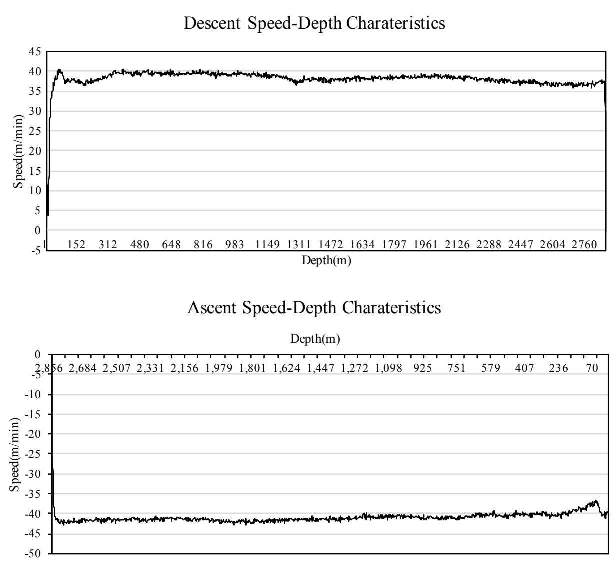

Fig. 7. Descent/ascent speed variations with respect to depth.

VI. Conclusion

The sea trial of a 7000m lander system was conducted in shallow water and deep-sea separately last year. The function of three kinds of release mechanism were validated its high reliability. Descent and ascent speeds were studied in different total weight conditions. Taking photos, recording videos, measuring environment parameters and sampling, representing the main ability of the lander system, were strictly and repeatedly tested. The overall system presented a satisfied performance and could be applied in hadal environment. Corresponding hadal deployments will be performed subsequently this year.

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