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AN ACOUSTIC SEA GLIDER FOR DEEP-SEA NOISE PROFILING USING AN ACOUSTIC VECTOR SENSOR

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ABSTRACT

An acoustic sea glider has been developed for ambient sea noise measurement and target detection through the deployment of an acoustic vector sensor (AVS). The glider was designed with three cabins connected in sequence and it can dive to depths exceeding 1200m. The AVS fixed on the glider measure acoustic pressure and particle velocities related to undersea noise, and the inner attitude sensors can effectively eliminate the estimation deviation of the direction of arrival. The inherent self-noises of the acoustic sea glider and AVS are presented respectively in respect to the Knudsen spectra of sea noise. Sea trial results indicate that the AVS could work well for undersea noise measurement when the glider is smooth sliding, and the target azimuth estimated by AVS after correction is remarkably consistent with the values measured by the GPS, and direction-finding errors are less than 10 degrees. The research in this paper shows that the acoustic sea glider is able to undertake tasks such as a wide range of underwater acoustic measurement and detection.

Keywords: acoustic sea glider; acoustic vector sensor; ambient sea noise; target detection

INTRODUCTION

The sea glider is a long-range autonomous underwater vehicle (AUV), utilising the buoyancy of sea water as the driving force and converting vertical motion to horizontal in conjunction with wings [1]. It can float upward and dive by only adjusting the density with very low energy consumption. Consequently, the sea glider can be much quieter and more energy-efficient compared to AUVs with propellers, since it is gliding instead of propelling [2].

Inherently, the temperature and salinity of sea water along with depth are the basic parameters of the ocean, and consequently conductivity, temperature and depth (CTD) sensors are the most widely used sensors in surveys of ocean physics. However, further intensive investigation for a better understanding of the ocean needs to be performed and more special sensors are being employed to collect various data. Low-frequency acoustic signals produced by tsunamis, undersea earthquakes, large mammals and artificial vessels are of increasing concern in the area of natural disaster monitoring and marine ecological protection [3],[4]. Moreover, the detection and identification of surface and underwater objects using acoustic sensors are another aspect of great concern in ship navigation [5],[6]. In order to achieve high-efficiency marine investigation and target detection, the integration of acoustic sensors on underwater moving platforms such as AUVs has become a new research hotspot [7],[8].

The acoustic sea glider, a kind of specially designed glider with low self-noise from machinery and electricity, is appropriate for acoustic sensors with their negligible hydrodynamic noise induced by low-speed motion [9],[10]. As a result, some acoustic sensors have been tentatively employed on the sea glider in the area of natural disaster monitoring and military surveillance [11]-[13].

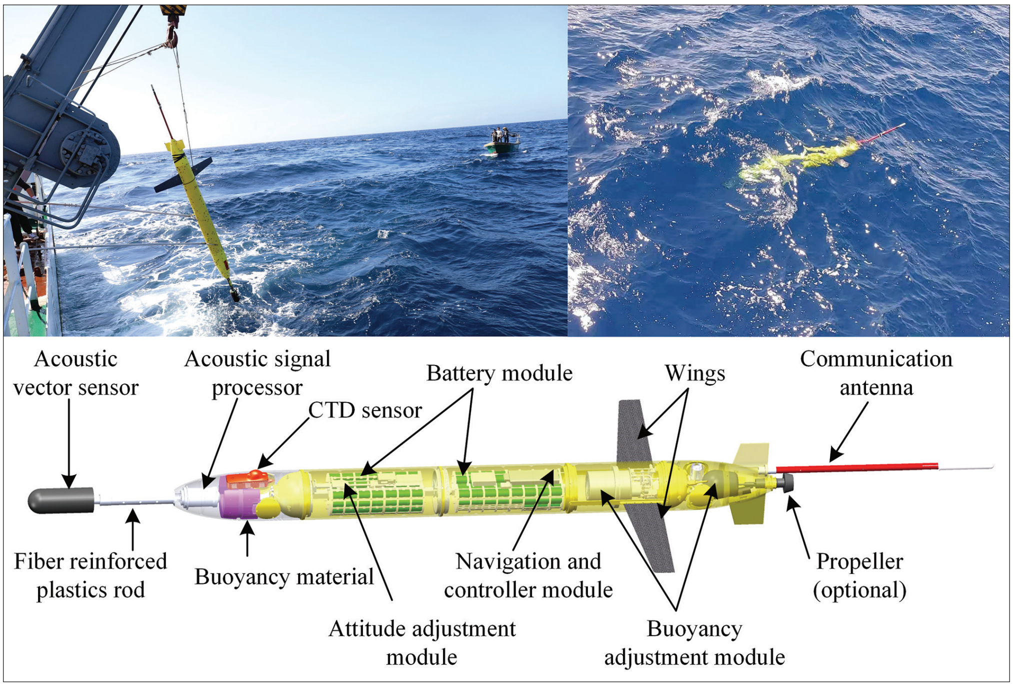

Fig. 1. Exploded view of the acoustic sea glider

Compared to acoustic pressure sensors or hydrophones, the acoustic glider based on acoustic vector sensors (AVS) shows great superiority in underwater acoustic measurement [14]. A single composite AVS measuring the acoustic pressure and particle velocities (acceleration, displacement or pressure gradient) synchronously can achieve a good signal-to-noise ratio of low-frequency acoustic signals instead of the conventional large-scale hydrophone array [15]. An AVS is insensitive to isotropic noise due to natural cosine directivities and it can be easily integrated on compact and lightweight underwater vehicles [16]. In terms of target detection, the direction of arrival of a target relative to the AVS can be estimated through acoustic intensity processing, and then the absolute bearing angle can be corrected using attitude information of the AVS relative to the geographic coordinate system.

This paper presents an acoustic sea glider equipped with an inertial-type AVS for deep-sea noise collection. The AVS design integrates one omnidirectional hydrophone, a triaxial accelerometer and the attitude sensors. The acoustic sensitivities and self-noise of the AVS were obtained through laboratory calibrations as well as the glider-radiated noise. Finally, the direction of arrival (DOA) estimation using the AVS on the acoustic sea glider was verified through a sea trial in the South China Sea.

GLIDER DESIGN

The acoustic sea glider is 3.2 m in length and 0.25 m in diameter. It is designed for the maximum diving depth of 1200 m with an endurance of 60 days at the average speed of one knot. The glider structure consists of three independent cabins as presented in Fig. 1.

The head cabin located at the front end of the glider is mainly for installing sensors, including an acoustic module, CTD sensors and buoyancy materials. The acoustic module includes a composite AVS with an acoustic dome and the related signal processor. The acoustic dome is made of polyurethane material to ensure the penetrability of sound waves and alleviate the influence of flow noise, and the AVS is flexibly suspended inside the dome with metal springs. The dome connects the head cabin through an aluminium alloy rod, to keep away from the disturbed stream. The acoustic signal processor, situated in the head cabin, is used to collect and store the output signals derived from the AVS. The whole head cabin is exposed to the water and all sensors and parts must be waterproof.

The middle cabin is divided into three separate pressurised compartments. A set of batteries and a drive mechanism are installed in the first compartment, constituting an attitude adjustment module, and hence the desired pitch angle of the glider can be achieved through the movement of batteries. In the second compartment there is a navigation and controller module, and another set of batteries is installed for providing extra electric power. A buoyancy adjustment module is located in the third compartment, and actually it works as an underwater oil pump that changes the buoyancy through filling in and pumping out the oil from the oilcan. A pair of carbon-fibre wings is fixed on the two sides of the third compartment for pitch attitude adjustment.

The tail cabin is immersed in the seawater just like the head cabin. An oil bag installed in this cabin is part of the buoyancy adjustment module. An iridium antenna for surface communications and a configurable propeller for providing short-term thrust are deployed outside the tail cabin.

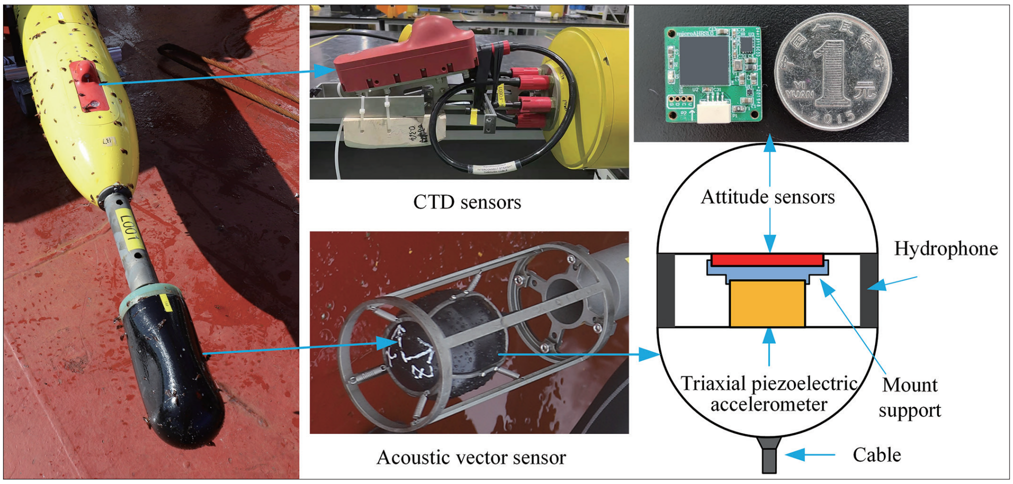

Fig. 2. CTD sensors and acoustic vector sensor

SENSOR DESIGN

The miniature and low-power CTD sensors (RBRlegato^3) are directly installed on the head of the sea glider with the probe exposed to the seawater, as shown in Fig. 2. Conventionally, the conductivity, temperature and depth data are recorded per second respectively. The composite AVS flexibly suspended inside the acoustic dome mainly consists of a hydrophone, a triaxial piezoelectric accelerometer and attitude sensors. The hydrophone and piezoelectric accelerometer sense the acoustic pressure and particle velocity respectively. The dimensions of the designed AVS are Ø66 × 78 mm with an average density of 1.15 g/cm^3. Test results indicate that the sensitivity of the hydrophone is –191.5 dB (0 dB re 1 V/μPa), and the sensitivities of the triaxial piezoelectric accelerometer are 2.85 V/g, with the equivalent pressure sensitivities of –179 dB (0 dB re 1 V/μPa at 1 kHz). The working bandwidth of the AVS can extend from 10 Hz to 3 kHz.

The underwater sea current will change the orientation of an AVS that is mounted on a moving platform, and consequently it is necessary to measure the real-time azimuth and attitude information of the AVS. Conventional countermeasures are directly installed on an electronic compass and an attitude sensor on the platform or vehicle. However, these methods may be less accurate because of the flexible suspension of the AVS and installation deviations of the attitude sensors. Therefore, attitude sensors are integrated into the AVS with acoustic sensors, and then the extended Kalman filter is used to achieve orientation correction during signal post-processing. The attitude sensors, including a triaxial MEMS gyroscope, a MEMS accelerometer and a MEMS magnetometer, measure the angular velocity, gravitational acceleration and magnetic flux density respectively. The attitude sensors are located on the circuit board which is supported on the piezoelectric accelerometer. The high-performance single-chip microcomputer based on an ARM-Cortex core on the same circuit board is used to achieve functions such as control, attitude data acquisition and angle calculation.

The attitude sensors' accuracies were tested at the First Metrology and Test Center of National Defense Technology Industry, China. Calibration frequencies were chosen as 0.1 Hz to 2 Hz since the motions induced by sea currents, tides and surges are conventionally below 1 Hz. Test results indicate that the measured heading and roll angle errors are less than 0.5° and the pitch angle error is less than 0.4° when the attitude angles do not exceed 20°.

Fig. 3(a) illustrates the self-noise characteristics of the AVS from 20 Hz to 4 kHz, and the Knudsen ambient sea noise levels at sea states 0 to 3 are also presented for comparison. The results show that the self-noise of the hydrophone is 36 dB/$\sqrt{\text{Hz}}$ at 1 kHz, which is lower than Knudsen's ambient noise of zero order sea level, and the self-noises of the vector channels gradually decrease and approach sea state 3 when the frequency is increased to 100 Hz.

In addition, the acoustically radiated noise from the acoustic sea glider was tested from 20 Hz to 4 kHz in the anechoic tank

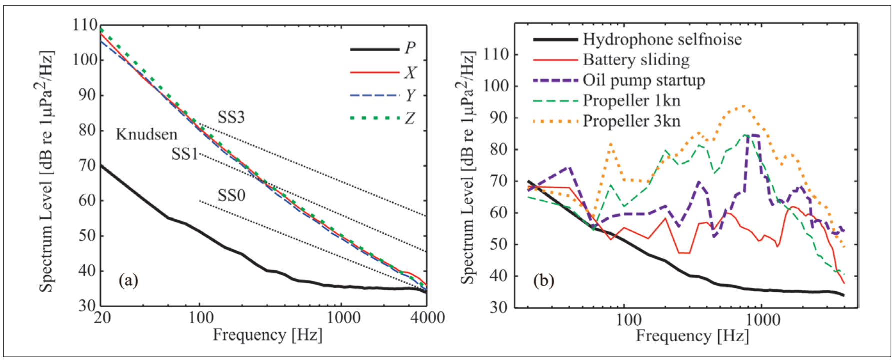

Fig. 3. Self-noise of AVS (a) and radiated noise from the acoustic sea glider (b)

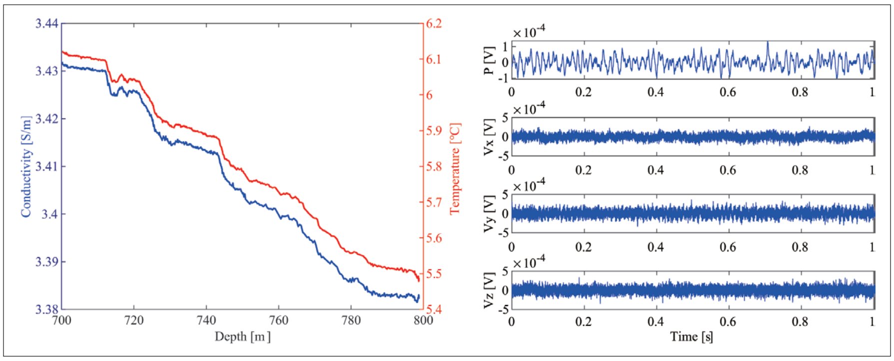

Fig. 4. CTD and ambient sea noise data collected through acoustic sea glider in the South China Sea

under different working conditions and the result is provided in Fig. 3(b). It is obvious that radiated noise from the glider under battery sliding is lower than other conditions, although it is almost 20 dB higher than the hydrophone's self-noise from 400 Hz to 3 kHz. When the oil pump starts up, the radiated noise increases as the noise peaks around 400 Hz and 1 kHz respectively. The propeller, used for emergency manoeuvres, has the most serious influence on the noise, and the peak noise level exceeds 90 dB at 700 Hz when sailing at 3 knots. The measured noise level below 100 Hz may be less accurate due to the size limitation of the anechoic tank.

SEA TRIAL

AMBIENT SEA NOISE GATHERING

Underwater noise measurement experiments were conducted based on the acoustic sea glider in the northern part of the South China Sea in May 2020. During the sea trial, the glider dived from the surface to a depth of 1000 m and the deep-water noise was recorded simultaneously. The conductivity and temperature at the depth from 700 m to 800 m are presented with a 1 Hz sampling rate as shown in Fig. 4, and hence the resulting sound velocity profile could be easily achieved. Acoustic ambient sea noises were faithfully recorded by the AVS under a 20 kHz sampling rate, benefiting from the lower background noise of the acoustic sea glider. The collected noise data related to the four sensors, i.e. the hydrophone and the triaxial piezoelectric accelerometer. Unlike the hydrophone (pressure sensor), acoustic particle velocity sensors (triaxial accelerometer) are more sensitive to high-frequency structure-borne noise, and hence low-pass filters are essential in the signal post-processing.

TARGET DETECTION EXPERIMENTS

The DOA of a target can be estimated through acoustic intensity processing. Acoustic intensity is generally a complex quantity that describes the propagating power associated with a sound wave in an acoustic medium, and it is mathematically expressed as the cross spectrum between the pressure and particle velocity in the frequency domain. Therefore the active intensity component that describes the transport of acoustic power can be used to determine the bearing of a sound source without ambiguity. During target detection experiments a scientific research ship, 42 m in length and 6 m in width, served as the target. The glider dived twice in total to depths of 579 m and 962 m respectively, and acquisition of the ship's radiated noise was executed by the AVS on the acoustic sea glider during the first dive. The outputs of the attitude sensors are presented in Fig. 5(a), and it can be observed that the underwater glider adjusts the heading frequently between −10° and 10°, making itself move forward as scheduled. Fig. 5(b) shows the azimuths of the target ship estimated by AVS with no attitude correction and veracious azimuths measured by the GPS from the time of 15:16 to 16:17; obviously, the glider's movement caused serious deviations. Fig. 5(c) shows the estimated azimuths after attitude correction (extended Kalman filter), which are very close to the values measured by the GPS, and the bearing accuracy achieved was better than 10°.

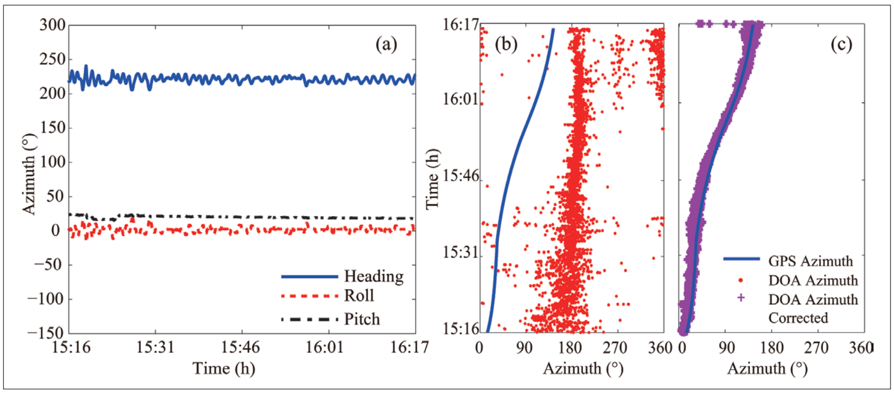

Fig. 5. Outputs of the attitude sensors when the glider is diving (a) and DOA estimation results before attitude correction (b) and after attitude correction (c)

CONCLUSIONS

Propeller-less propulsion and stable movement make the sea glider the perfect underwater moving platform for various acoustic measurements. A dedicated acoustic sea glider was developed for underwater wide-range measurements of ambient sea noise and vessel-radiated noise in this paper, through incorporating an inertial-type acoustic vector sensor (AVS). The AVS located at the front end of the glider successfully measured underwater noise relating to sound pressure and particle velocity together with attitude angles. Test results in the anechoic tank show that the AVS has comparatively low self-noise, and the radiated noise is acceptable when the acoustic sea glider is sliding. Sea trial results demonstrated that the AVS worked well when the acoustic sea glider was diving from the surface down to the deep sea. The bearing accuracy of the target through the AVS on the sea glider is better than 10° after attitude correction. This research is of important significance for the application of AVS on acoustic sea gliders, and moreover underwater observation could be more effective in both the military and civilian fields with the employment of a sea glider cluster and various acoustic sensors.

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