A Pneumatic-driven Airdropped Portable Underwater Profiler for Rapid Deployment

Xiaole Xu
The State Key Laboratory of Fluid Power Transmission and control
Zhejiang University
Hangzhou, China
xuxiaole@zju.edu.cn

Canjun Yang
The State Key Laboratory of Fluid Power Transmission and control
Zhejiang University
Hangzhou, China
ycj@zju.edu.cn

***Abstract*— This paper puts forward a new underwater profiler. The mass of the whole machine is about 7Kg, with smaller volume. It can be air-dropped and suitable for fast deployment, as well as uses pneumatic method to adjust buoyancy, which is reliable with low cost, and can be used for a large scale of deployment. Its attitude can be adjusted throughout modulating barycenter, and with the assistance of wings, water power is utilized for path planning and achieve localized or larger range of supervision. The biggest dive depth is 1000m, in which situation 50 times' profile survey can be achieved, and it is suitable to be applied for emergent maritime search and rescue, etc.**

Keywords— pneumatic-driven; airdropped; profiler

I. INTRODUCTION

Profiler is mainly used for the profile survey of the sea. The cable-type profiler appeared earlier, and its high reliability makes it still play an important role by now. For more mature ones, there is McLane Moored Profiler (MMP) which is mainly applied in observation network at the bottom of MARS. As a part of observation network at the bottom of MARS[1]. MMP can conduct profiling motion on a fixed cable, and its drive for profiling motion still depends on buoyancy control, with brake at the location of cable connection, to make MMP able to quickly stop at the appointed place as well as observe and measure sea with certain depth. MMP is 131cm long, 33cm wide and 55cm thick, and the weight in air is 71kg, and the biggest working depth is 6000m. Non-cable profiler is convenient for placement and application, and the profilers that are widely used include APEX[2]、SOLO[3] and Air-Sea Interaction Profiler(ASIP)[4]. APEX is distributed widely, with the biggest working depth of 2000m and weight of 25Kg. It mainly changes buoyancy by a single-stroke plunger pump. ASIP is mainly used for profiling observation of the shallow sea, and takes the propeller propulsion technique to realize profiling motion. On the bottom of the ASIP, it is equipped with a propeller with a complex pressure sensor. With the cooperation of corotation and inversion of the propeller, ASIP can realize accurate control on the vertical depth. These profilers have mature technology, advanced performance, but generally large volume and high cost. Once, in order to verify the algorithm, Virginia Tech built a pneumatic profiler, but the designed depth is only 100 m, with shorter endurance[5]. In order that profiler is placed with a large scale in a particular situation, this paper puts forward a smaller pneumatic profiler design scheme.

II. PROFILER DESIGN AND WORKING PROCEDURE

Profiler machine is shown in fig.1, and is divided into four sections from top to bottom: the buoyancy regulation sector, sensor and control sector, power reserve sector, airdrop sector. Besides, the stretched slender bar is antenna, hull and gas cylinder by bonding connection are used to adjust the stable and variable wings and tail.

Buoyancy regulation sector is on top, and its main working mechanism of changing buoyancy is that in deep sea, it uses high pressure air to drive gas piston so as to increase buoyancy and realize the floatation, and on the water surface, it uses spring drive the piston to reduce buoyancy and realize sinking. Using the high pressure gas can avoid the energy waste of a single-stroke plunger pump or hydraulic pump in the deep sea, and reduce the battery to carry. A small amount of high pressure gas in deep sea can fully sweel to trigger large net buoyancy on the sea-surface, so as to raise the antenna. At the same time, the pneumatic circuit is simple, with low cost, and single air bottle can realize about 50 times' work cycle. Considering the structure, antenna is placed on the end same with buoyancy regulating, directly connected to the piston. The connection of antenna and control circuit is sealed. When the buoyancy is the biggest on the surface, the antenna height also gets higner accordingly, improving the communication success rate in the severe sea condition.

The shell of sensor and control sector uses carbon fiber, and the hull is fully sealed. In order to prevent carbon fiber hull end from failure in water, two ends use aluminum alloy block. Sensing and control part uses MSP430F149 chip of low power consumption as a controller, with the multiple sensors including temperature, pressure, water. Through a relay and a high-speed electromagnetic switch valve, the pneumatic circuit is regulated, and the two steering gears

978-0-933957-43-5 ©2015 MTS

are controlled to change the machine's barycenter and attitude.

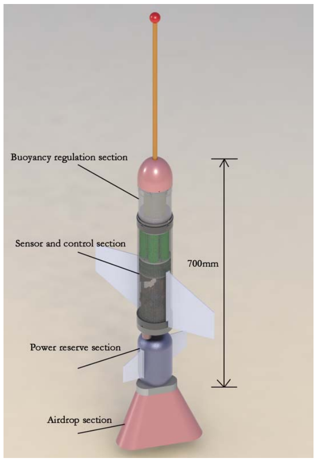

Fig. 1. the pneumatic-driven airdropped underwater profiler

Power reserve device is placed in the lower position, and the main component is a carbon fiber aluminum alloy composite high-pressure cylinder, with air of 30 MPa pressure as power source stored in it. Carbon fiber cylinder directly contacts with the sea water, reducing the sealing length and the mass of the whole machine.

Airdrop device is placed on the bottom of the machine, and mainly adopts DJI Dropsafe as main part. Parachute and high-pressure gas cylinder is spliced by polyvinyl acetate, and this kind of splice is dissolved as long as getting access to water, which can realize that the parachute is automatically separated after falling into water. In the process of descend, the parachute is at the top of the machine, that is to say, the antenna will be the first to enter the water, reducing the impact.

For underwater profiler can resist the effect of ocean current and a long-term fixed-point ocean profile data of dynamic monitoring can be conducted in a fixed sea area. The machine is equipped with the barycenter control system. By adjusting the barycenter, it can realize attitude adjustment, to make the profiler quickly conduct longitudinal profiling motion and use the way of underwater glider to make profiler with the horizontal movement. In order to achieve a long-time measurement and convenient control, the Newton Euler's equation is needed to establish the dynamics model of the profiler, and optimize the model to guide the mechanical design.

The single working cycle of the profiler is shown in fig. 2, mainly including: placement, diving monitoring and position adjustment, grounding, rising monitoring and position adjustment, communication. Profiler uses air drop (also can use ship to place). After being air dropped over the target area, the parachute is used to fall on the sea surface with the speed of not higher than 6 m/s, and the parachute is separated from the machine. Then profiler gets the target bearing and instruction through iridium and shore-based monitoring station communication, , and compares the target bearing with the current position determined by GPS, controls attitude, adjusts buoyancy for diving or floating,

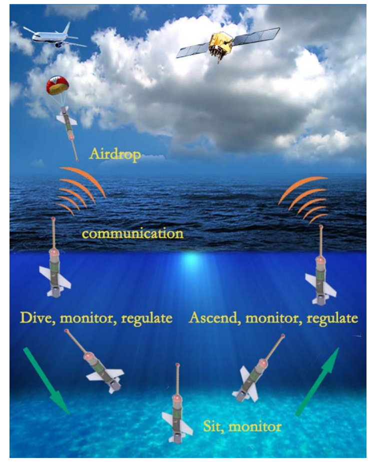

Fig. 2. the pneumatic-driven airdropped underwater profiler

and moves towards the target bearing with hydrodynamic drive.

In the process of the diving, grounding and rising, profiler always monitors the target data (underwater sound, temperature and depth).

All parameters of the machine are shown in Table 1.

Table 1. Specifications of the profiler

Parameter	Value	Units
Maximum depth	1000	m
Endurance	About 50	cycles
Mass	7 without parachute	Kg

III. Structural Design

Pneumatic profiler is still in the optimization design, and the previous version that has passed the lake experiment temporarily is not equipped with pneumatic drive module (using motor drive instead, mainly used for validation of hydrodynamic performance), pneumatic drive module has passed the test alone, in the introduction of the structure design of this sector, the optimization version of the latest design shall prevail.

A. buoyancy regulating system

Buoyancy regulating system is shown in figure 3 and the system is placed at the top of the whole machine. Its main principle is to push the piston to move up and down through the high pressure gas, so as to change the volume of the whole machine, to change the buoyancy of the whole machine. The thickness and shape of the piston and the external hull are specially designed, and in the situation to satisfy the requirement of design pressure, it achieves less weight as far as possible. Piston can withstand the maximum water depth of 1000m, equal to 10 MPa pressure, so the requirement for the thickness is greater. The piston cylinder's inside and outside pressure is always in balance, so the wall thickness is small, only used as structural components. Under water, high-pressure gas enters from the air inlet, to push the piston upward, and compress spring at the same time, then the volume of the whole machine gets larger to achieve ascend. After reaching the sea surface, the air valve open, and spring reset function is used to discharge the gas, reduce the buoyancy and then realize sinking when it need to descend. Antenna and the buoyancy regulating system are placed on the same side of the machine, the antenna is fixed on the piston, and they are connected by the retractable line and the control circuit of hull. In the whole design, the choice of the spring is very important. Spring has two main functions. One is to control air inflation speed in the process of air inflation, the other is to play the role of restoration when the water needs to reduce volume. Spring is mainly affected by gas pressure, seawater pressure and friction force, in which the gas pressure and seawater pressure can be controlled or measured, the friction between piston and hull needs to be further confirmed.

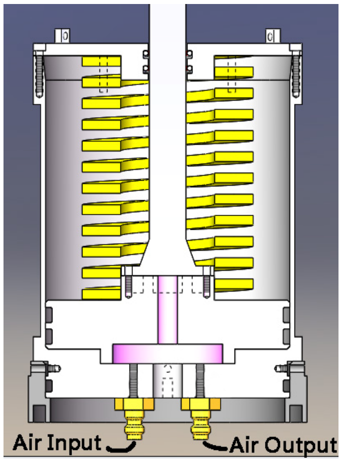

Fig. 3. the structure of the buoyancy regulating system

Because the pressure difference is bigger, the sealing design must add baffle ring, the maximum tensile amount of external sealing shall not exceed 6%, the surface roughness of the inner diameter of piston cylinder needs to be less than 0.8. With the comprehensive consideration of various factors, the initial compression 10% would be more appropriate, with Shaw A90 hardness of sealing ring, the radial clearance is less than 0.05 mm. In the seal design process, guide cone shall be added. By checking table, it can be gained compression force is 10 N/cm, the friction coefficient of rubber ring and aluminum alloy is 0.75, the friction force is:

$$F = 10N/cm*2*3.14*4*0.75 = 188N \qquad (1)$$

According to the structural design, the free length of the spring is about 100 mm, the compression quantity is about 50 mm, with Japan Datong spring YEL70-100. The stiffness is about 80 N/mm, the maximum elongation to control spring is approximately 97 mm, which will ensure spring is always in a state of compression.

B. Pneumatic control system

The pneumatic control circuit of the whole machine is shown in fig.4. Through this circuit, the quantitative intake and exhaust of gas can be achieved, of which the quantitative intake of gas is more difficult, there are two kinds of traditional gas quantitative control method, one is to use the flow valve to control the gas intake, the other is to use the position sensor to detect the position of the piston to indirectly control the gas intake. The pressure of the gas used in this design reached 30MPa, it is difficult to find the flow valve with an acceptable volume and weight, as for the method using position sensor, the sealing and structural design are relatively difficult, so this design indirectly achieves the determination of the gas intake by the method of using the pressure sensor to detect the pressure of the gas cylinder.

The whole pneumatic circuit is very simple, two high-speed solenoid valves respectively connect with the gas cylinder and the outside directly, controlling the intake and exhaust of gas of the piston cylinder. Because the speed of the movement of the valve is very fast (only 30ms from fully open to fully close), through the actual test, accurate control can be achieved to the intake and exhaust of gas. In practical application, every time when rising underwater , the piston cylinder will intake 20ml, 10Mpa gas or the same amount of gas, these high-pressure gas rise along with the profiler , as the outside pressure decreases, it will gradually expand. There is a pressure sensor always monitoring the pressure of the gas in the gas cylinder, through comparing the change of pressure before and after one action , the gas intake of the piston cylinder can be calculated. Of course, the gas intake obtained in this way is only an estimate value, but in this design, the estimate value has met the design requirements, the following calculation shows that this estimate is feasible.

The process of the gas charging by the gas cylinder to the piston cylinder is considered as an adiabatic process, according to the deduction of the ideal gas property, the following equation can be obtained：

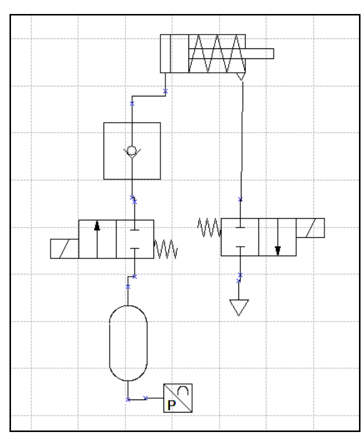

Fig. 4. The pneumatic control circuit

$$TV^{k-1} = C$$

Namely

$$T_1 V_1^{k-1} = T_2 V_2^{k-1}$$

of which: T_1、V_1、T_2、V_2 is the state before and after a certain action，Thereby it can be deducted that：

$$\frac{T_1}{T_2} = \frac{V_2^{k-1}}{V_1^{k-1}} = (\frac{V_2}{V_1})^{k-1} \quad (2)$$

1) Calculation of pressure change

The valve will be closed after one action, assume that the temperature is not yet conducted, then

$$P_1 V_1 = v_1 R_1 T_1$$

$$P_2 V_2 = v_2 R_2 T_2$$

It can be deducted that

$$\frac{P_1}{P_2} = \frac{\frac{v_1 R_1 T_1}{V_1}}{\frac{v_2 R_2 T_2}{V_2}} = \frac{v_1}{v_2} \times \frac{T_1}{T_2} = \frac{v_1}{v_2} \times (\frac{V_2}{V_1})^{k-1} \quad (3)$$

It can be seen that each time before and after the close of the valve, the pressure relative change is different, but it can be calculated, if we want to control the position of the piston cylinder by measuring the pressure difference, then even when the value $\frac{P_1}{P_2}$ obtained is minimum , this value can still be measured. Next, we will explore when the minimum value of $\frac{P_1}{P_2}$ can be obtained.

Because the quality and volume of the gas discharged each time is constant, we can get:：

$$v = v_1 - v_2$$

$$20ml = V_2 - V_1$$

then:

$$\frac{P_1}{P_2} = \frac{v_2 + v}{v_2} \times (\frac{V_1 + 0.02}{V_1})^{k-1} \quad (4)$$

That is to say, when the pressure inside the gas cylinder is 30MPa from the very beginning, the minimum value of $\frac{P_1}{P_2}$ can be obtained, at this point：

$$\frac{P_1}{P_2} = \frac{3300 + 20}{3300} \times (\frac{1.1 + 0.02}{1.1})^{1.4-1} = 1.013$$

That is to say, there is a still 1.3% pressure difference at this moment, though this pressure difference is not great, with an existing pressure sensor, in the case where the high accuracy is not required, it can be measured completely.

2) Explanation

If the temperature change is not considered, the variation range of the pressure is, still within the measurable range, concerning that whether the value should be chosen as 0.6% or 1.3% or the other between the both, it needs to be obtained by calibration and experiment.

In the calculation of the number of work, we can use the law of conservation of matter, theoretically as many as 110 profile cycles can be obtained, of course, taking into account the leakage and heat loss, it is very difficult to achieve 110 working times.

C. Self balancing system

With the increase in the number of sections, the gas in the cylinder will be consumed, resulting in the weight change can reach up to about 250g, which can not be ignored. so the specific mechanism is designed to realize the Self balancing of the whole machine when gas in the cylinder is reduced . Self balancing system can not completely balance the whole machine, but the changes in weight caused by gas consumption can be reduced to an acceptable range, the main structure of it is shown in the following diagram.

The principle of self balancing is mainly that, the pressure is lowered after the gas consumption, the pressure decreases, more seawater will be pressed in, which reduces the buoyancy of the whole machine, the automatic control of the buoyancy is realized.

IV. THE DYNAMICS DODELING

The underwater dynamic modeling of the profiler is carried out in the body coordinate system of the profiler, which is used to analyze the actual gliding angle when the profiler is gliding steadily underwater, so as to evaluate the ability of the profiler to correct the horizontal displacement . In order to obtain the angle of steady gliding of the profiler, the steady state model is described by three equations, which are respectively the force balance in the Zb and Xb directions , and the torque balance in the Yb direction of the body coordinate system of the profiler.[6]

$$\begin{cases} X_b: D(v,a) = \left[(m_1 + m_2)g - F_{buoyancy}\right] \cdot cos\theta \\ Z_b: L(v,a) = \left[(m_1 + m_2)g - F_{buoyancy}\right] \cdot sin\theta \\ Y_b: M(v,a) = -m_1 g a_1 sin\theta - m_2 g(a_2 sin\theta + b_2 cos\theta) \end{cases} \quad (5)$$

Among which: $D(v,a)$、$L(v,a)$、$M(v,a)$ respectively the axial resistance, the raising force vertical to the axial direction and the coaxial torque to which the profiler is subjected in the water.

$$\begin{cases} D(v,a) = 0.5 * k \cdot v^2 \cdot C_d(\alpha) \\ L(v,a) = 0.5 * k \cdot v^2 \cdot C_l(\alpha) \\ M(v,a) = 0.5 * t \cdot v^2 \cdot C_m(\alpha) \end{cases} \quad (6)$$

Of which, k, t is the de-dimensional parameters, k=2kg/m、t=2kg, they are respectively resistance, raising force and water resistance coefficient of torque, which are obtained by the calculation of FLUENT software.

V. EXPERIMENTAL RESULT

The whole set of pneumatic profiler is in the process of continual optimization, but the sub-module test has been completed, among which, the hydrodynamic experiment has verified the possibility of localization under the passive condition through the wings and tail, the hitting and pressing experiments of carbon fiber has verified the availability of carbon fiber hull, the pneumatic test has verified the feasibility of the pneumatic control.

Fig. 5. the lake experiment for water dynamic test

The lake experiment prove that the water dynamic model of the profiler is feasible. In this test version of the profiler, GPS, attitude sensor, compass are installed to monitor the status. Long-wave communication is used for control. The profiler can hover at a specfic depth and make a turn with a certain degree. With the help of barycenter adjustment and wings, it can make for appointed direction.

The pneumatic test was conducted individually for safety considerations. Necessary sensors was installed and a weight was used to instead of water pressure. The high-speed electromagnetic switch valve works well and 50 working cycles can be accomplished.

VI. Conclusion

This paper presents a type of pneumatic regulating buoyancy underwater profiler which can be airdropped for distribution. High pressure gas is used to drive the profiler. Special designed piston and its's relevant parts can change the buoyancy. Carbon fiber hull reduce the weight. Barycenter system and wings is used to make sure the profiler can reach a specific location. The sub-module test has been completed and the feasibility of it has been verified , and soon the test of the whole machine will be carried out.

Fig. 6. The Pneumatic Test

References

[1] Morrison III, Archie T., John D. Billings, and Kenneth W. Doherty. "The McLane Moored Profiler: An autonomous platform for oceanographic measurements." In OCEANS 2000 MTS/IEEE Conference and Exhibition, vol. 1, pp. 353-358. IEEE, 2000.

[2] Sanford, Thomas B., John H. Dunlap, James Carlson, Douglas C. Webb, and James B. Girton. "Autonomous velocity and density profiler: EM-APEX." In*Current Measurement Technology, 2005. Proceedings of the IEEE/OES Eighth Working Conference on*, pp. 152-156. IEEE, 2005.

[3] Mitchell, B. Greg, Mati Kahru, and Jeff Sherman. "Autonomous temperature-irradiance profiler resolves the spring bloom in the Sea of Japan." *Proceedings, Ocean Optics XV, Monaco* (2000).

[4] Ward, Brian, and Tim Fristedt. "Air-sea interaction profiler: Autonomous upper ocean measurements." In *US/EU-Baltic International Symposium, 2008 IEEE/OES*, pp. 1-8. IEEE, 2008.

[5] Wolek, Artur, Jack Burns, Craig Woolsey, Jake Quenzer, Laszlo Techy, and Kristi Morgansen. "A maneuverable, pneumatic underwater glider." In *Oceans, 2012*, pp. 1-7. IEEE, 2012.

[6] Arima, M., N. Ichihashi, and Y. Miwa. "Modelling and motion simulation of an underwater glider with independently controllable main wings." In *OCEANS 2009-EUROPE*, pp. 1-6. IEEE, 2009.