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# Design and research on a variable ballast system for deep-sea manned submersibles

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**Abstract:** Variable ballast systems are necessary for manned submersibles to adjust their buoyancy. In this paper, the design of a variable ballast system for a manned submersible is described. The variable ballast system uses a super high pressure hydraulic seawater system. A super high pressure seawater pump and a deep-sea brushless DC motor are used to pump seawater into or from the variable ballast tank, increasing or decreasing the weight of the manned submersible. A magnetostrictive linear displacement transducer can detect the seawater level in the variable ballast tank. Some seawater valves are used to control pumping direction and control on-off states. The design and testing procedure for the valves is described. Finally, the future development of variable ballast systems and seawater hydraulic systems is projected.

**Keywords:** deep-sea; manned submersible; variable ballast system; weight; seawater pump; seawater hydraulic system

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## 1 Introduction

As the population on the earth explodes, the resources supplied from the land approach the limit. Many countries have focused their attention of economic development on the sea. This is because there are very rich resources in the sea including water, energy, mineral and biology, etc. Deep-sea explorations are indispensable not only for the investigation of marine creatures, microorganisms, minerals and other resources hidden under the deep water, but also for the geophysical research into the structure and behavior of the earth[1].

## 2 Manned submersible

Manned submersible is a very important means for deep-sea exploration. Fig.1 shows a typical deep-sea manned submersible configuration. The missions set for deep-sea manned submersible are that it can fulfill the following tasks:

1) To carry scientists, engineers and their various instrument and tools to the deep sea to perform tasks of oceanic geography, oceanic physics, oceanic biology and oceanic chemistry.

2) To investigate sulfide and cobalt encrustation resources. By underwater mini-drilling tools, the core sample of the cobalt can be obtained.

3) To explore and locate the hydrothermal vent, measure the temperature at the center of active hydrothermal vents, and take the water sample and keep it with constant temperature and pressure.

4) To effectively perform the sampling of the deposits, suspended creatures and microbes at the required locations.

5) To deploy the underwater devices in the specific location, inspect the cables and pipelines, and perform other difficult tasks such as recovering wrecks[2-3].

During a dive, the total weight of the submersible often varies because of the change of the load in the scientific basket or the difference of seawater density at different depths or regions, which is able to be balanced by the variable ballast （VB） system. The VB system is designed to allow the pilot to adjust the weight of the submersible while deep in the sea.

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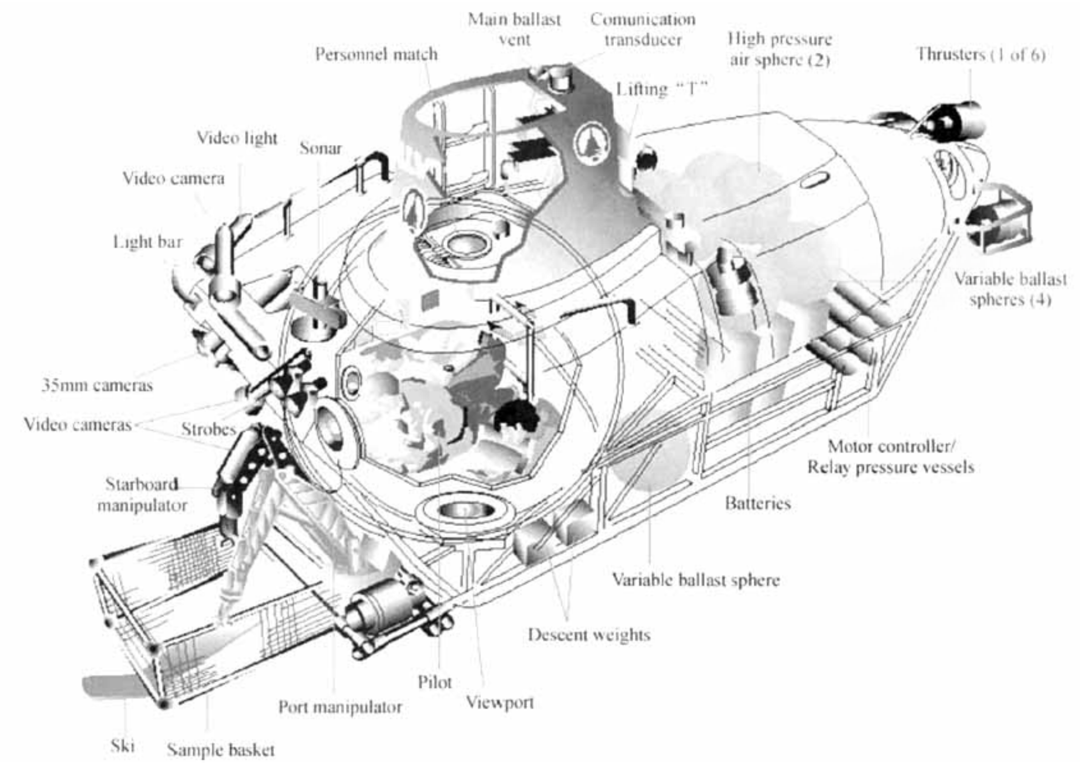


Fig.1 A deep-sea manned submersible

## 3 Design & research of VB system

### 3.1 Primary characteristics

The system is composed of a VB tank, i.e. a pressure vessel, and a super high pressure seawater pump, a DC-motor and some seawater change-over valves. The seawater is charged into or discharged from the VB tank to finely adjust the weight of the submersible so as to move on and off the sea bottom.

### 3.2 System design

The VB system in Fig.2 is composed of VB tank 1, oil-pilot-operated stop valves *A*, *B*, *C*, *D* and *E*, seawater level transducer 2, filter 3, check valve 4, pressure balance valve 5, safety valve 6, seawater pump 7, DC-motor 8 and pipe system 9. The system can work in the maximal 700 0 meters underwater. Its buoyancy adjusting range is 0 to 300 kg.

Charging process: with oil-pilot-operated stop valves *B* and *C* actuated, seawater is pumped from the sea, through the filter, valve *C*, seawater pump, pressure balance valve, check valve, valve *B*, and to the VB tank. Discharging process: with oil-pilot-operated stop valves *A* and *D* actuated, seawater is pumped from the VB tank, through *A*, seawater pump, pressure balance valve, check valve, valve *D*, filter, and into the sea. The check valve symbol is inside the seawater pump symbol to indicate that, with valve *C* actuated, the check-valve-type pump allows sea pressure through the pump up to the pressure balance valve.

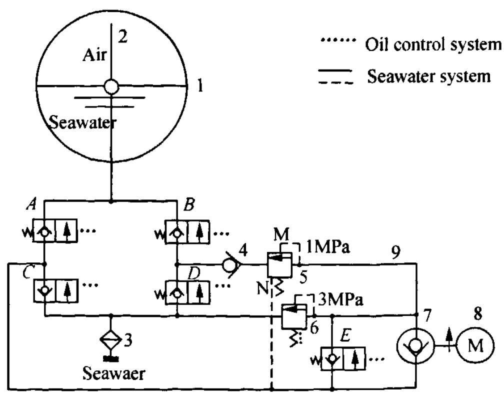


Fig.2 VB system

### 3.3 System composing

3.3.1 VB tank

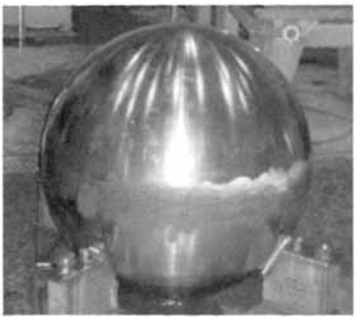

Fig.3 VB tank

The VB tank in Fig.3 is a global pressure vessel and can endure external pressure difference to 71 MPa. Titanium alloy is used for all parts. Its capacity is about 310 L, and its internal pressure varies with the feed seawater volume, about 0 to 3 MPa at most. It has two connectors connecting with pipe system and seawater level transducer.

3.3.2 Seawater level transducer

The seawater level transducer is a magnetostrictive linear displacement transducer. It has a plus-buoyancy ball that can move up and down with the seawater level in the VB tank. Different voltage value accords with different seawater level, so the pilot can know real-time seawater level in the VB tank.

3.3.3 Seawater pump

The seawater pump in Fig.4 is the basis of the seawater-type VB system, designed to meet submersible's working depth requirement of 7 000 m. This check-valve-type piston pump is a good seawater pump with light weight and small size, and also can pump against a pressure difference to 72 MPa.

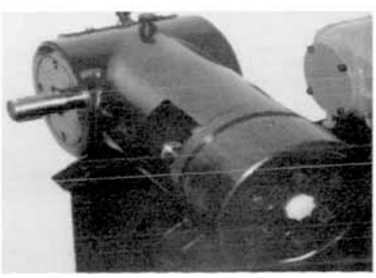

Fig.4 Seawater pump

Because of this high discharge pressure, the pump must be piston-type. To minimize wear when pumping silt-laden water, this piston pump is constructed with solid ceramic cylinder liners and steel pistons coated with a titanium alloy dioxide ceramic. Titanium alloy is used for all other parts that come into direct contact with seawater. The low-pressure, wiper-type seals in each cylinder liner separate the lubricating oil in the pump drive housing from the seawater being pumped[4-5].

3.3.4 DC-motor

An 8 kW, 110V DC brushless motor in Fig.5 is used to drive the seawater pump. The motor is ocean-pressure-compensated to permit use of thin-wall lightweight housing. Its working speed can be regulated from 0 to 1 450 r/m. Titanium alloy is used for all parts that come into direct contact with seawater[6].

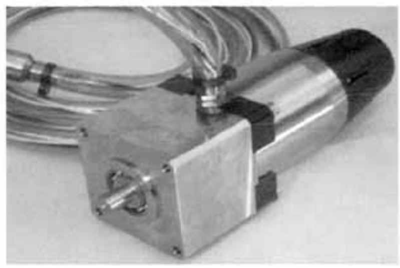

Fig.5 Deep-sea brushless DC motor

3.3.5 Oil-pilot-operated stop valve

Five 2-way, oil-pilot-operated stop valves in Fig.6 provide switching and shutoff functions. These 2-way valves have a unique poppet design that enables the valves to maintain drip-tight sealing even when 71MPa-pressure seawater is applied to the input port. They can open at 71 MPa line pressure with the pilot pressure signal of 19 MPa. The valves are of titanium alloy to resist corrosion, and for light weight and high strength.

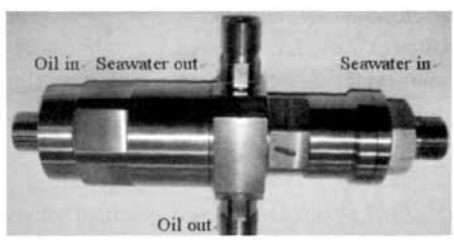


Fig.6 Oil-pilot-operated stop valve

Before the stop valves were installed on the VB system, they were successfully evaluated in land. Table 1 shows the results of seal and pilot-operated capability tests.

The valve *E* is a bypass valve, and is open when the seawater pump is started, enabling the pump-driven motor to start under no-load.

**Table 1 Oil-pilot-operated stop valves test results**

| SN | Test item | Test pressure/MPa | Result |
|---|---|---|---|
| | Hydraulic oil seal | 25 | OK |
| | Seawater in-out seal | 71 | OK |
| *A* | Disc seal | 0.1 | OK |
| | Pilot-operated | 19(pilot) | OK |
| | | 71(seawater) | OK |
| | Hydraulic oil seal | 25 | OK |
| | Seawater in-out seal | 71 | OK |
| *B* | Disc seal | 0.1 | OK |
| | Pilot-operated | 19(pilot) | OK |
| | | 71(seawater) | OK |
| | Hydraulic oil seal | 25 | OK |
| | Seawater in-out seal | 71 | OK |
| *C* | Disc seal | 0.1 | OK |
| | Pilot-operated | 19(pilot) | OK |
| | | 71(seawater) | OK |
| | Hydraulic oil seal | 25 | OK |
| | Seawater in-out seal | 71 | OK |
| *D* | Disc seal | 0.1 | OK |
| | Pilot-operated | 19(pilot) | OK |
| | | 71(seawater) | OK |
| | Hydraulic oil seal | 25 | OK |
| | Seawater in-out seal | 71 | OK |
| *E* | Disc seal | 0.1 | OK |
| | Pilot-operated | 19(pilot) | OK |
| | | 71(seawater) | OK |

The valve *E* is a bypass valve, and is open when the seawater pump is started, enabling the pump-driven motor to start under no-load.

3.3.6 Check valve

The check valve in the circuit provides backpressure surge protection to the pressure balance valve. The valve is of titanium alloy and its opening pressure is about 0.1 MPa.

3.3.7 Pressure balance valve

The pressure balance valve in Fig.7 is a focus in the system design and its opening pressure is about 1 MPa. That is, the valve will not be opened until the pressure difference between M and N is more than 1 MPa.

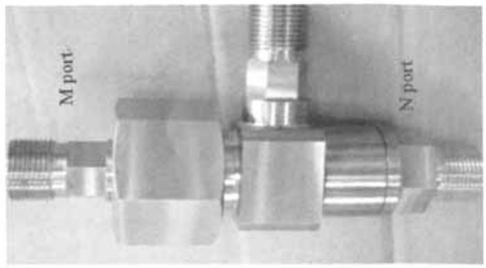


Fig.7 Pressure balance valve

The pressure balance valve can sense inlet pressure to the seawater pump, then add that inlet pressure to a spring force equivalent about to 1 MPa that the seawater pump must overcome. The valve forces the seawater pump to "control" flow through the system. Assume, for example, that the VB tank is at 0.2 MPa and to be filled; ambient ocean pressure is 30 MPa. If the pressure balance valve were not in the system, seawater would rush freely through the check-valve-type seawater pump into the VB tank, filling it completely. In this instance, the seawater pump inlet pressure is 30 MPa. Because this is a check-valve-type pump, seawater at 30 MPa flows through the seawater pump and is sensed at the inlet to the pressure balance valve. The pressure balance valve also senses 30 MPa at the inlet to the seawater pump. Thus, 30 MPa is acting on both sides of the pressure balance valve piston, and the seawater pump must overcome only 1 MPa spring force to create flow across the pressure balance valve. During steady state pumping, with the pressure balance valve keeping open, pressure at the pressure balance valve outlet is 31 MPa, pumping against 1 MPa through the seawater pump.

On the other hand, assume that the VB tank is at 3MPa (its usual maximal pressure) and is to be emptied; the ambient ocean pressure is 30 MPa. When the seawater pump starts, the seawater pump inlet and outlet pressures are 3 MPa, and 3 MPa is acting on both sides of the piston of the pressure balance valve. The pressure balance valve piston bottoms when seawater pump pressure reaches 1 MPa (actually 4MPa in the line), opening the pressure balance valve fully. However, flow through the check valve does not start until the seawater pump pressure reaches 27 MPa (30 minus 3), with actual line pressure being 30 MPa.

Before the pressure balance valve was installed on the

VB system, it was successfully evaluated in land. Table 2 shows the results of open and re-seating seal capability tests.

**Table 2 Test results of pressure balance valve**

| *N* pressure/MPa | Open pressure/MPa | Re-seating seal | Results |
|---|---|---|---|
| 0 | 0.9 | Good | OK |
| 10 | 1.0 | Good | OK |
| 20 | 1.1 | Good | OK |
| 30 | 1.0 | Good | OK |
| 40 | 1.2 | Good | OK |
| 50 | 1.1 | Good | OK |
| 60 | 1.0 | Good | OK |
| 71 | 1.1 | Good | OK |

3.3.8 Safety valve

The safety valve prevents overpressure of the seawater pump. The valve is of titanium alloy and its blow pressure is about 3 MPa. In order to reduce spring's force and valve's weight, its outlet is opened to the ocean, so the blow pressure is 3MPa, instead of 73MPa. Thus, the maximum pressure at seawater pump outlet is actually always less than 73 MPa (70 plus 3).

Before the safety valve was installed on the VB system, it was successfully evaluated in land. Table 3 shows the results of blow and re-seating seal capability tests.

**Table 3 Test results of safety valve**

| Back pressure/MPa | Blow pressure/MPa | Re-seating seal | Result |
|---|---|---|---|
| 0 | 2.8 | Good | OK |
| 10 | 2.9 | Good | OK |
| 20 | 2.9 | Good | OK |
| 30 | 3.0 | Good | OK |
| 40 | 2.9 | Good | OK |
| 50 | 3.1 | Good | OK |
| 60 | 3.0 | Good | OK |
| 71 | 3.1 | Good | OK |

3.3.9 Filter

The seawater filter, 40 μm, of titanium alloy material, is a standard strainer type. It is in a titanic housing with a screened opening that prevents seaweed and small fish from fouling the filter. Seawater is taken in through the filter, then passes through the seawater pump, and then into the VB tank. When the VB tank is pumped out, the path is reversed, flushing the filter in the process.

3.3.10 Pipe system

All pipes, of pure titanium material, can endure external pressure to 71 MPa.

### 3.4 Oil HPU for remote control

The controls which operate the seawater stop valves in the system is submersible's standard underwater oil HPU. Oil hydraulics is used in the control system because seawater hydraulics is not developed sufficiently to perform so delicate control functions.

### 3.5 System evaluation

Before the system was installed on the submersible, it was successfully evaluated in land test and in an ocean simulation environment with pressure equivalent to 7000 m. System's water charging and discharging functions can be normally realized at the ambient pressure 71 MPa. Fig.8 and Fig.9 show the system's simulation test scenes. Table 4 shows the results of simulation test.

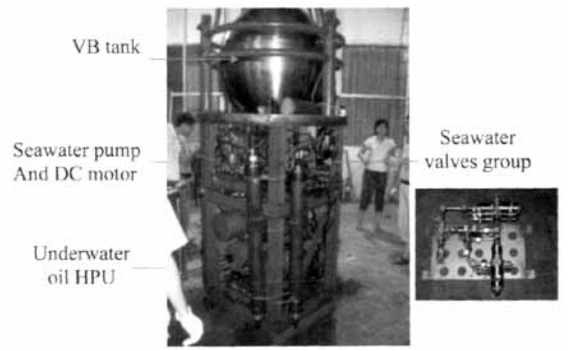


Fig.8 VB system test in land

Fig.9 VB system simulation test scene

Table 4 System simulation test results

| Environment pressure/MPa | Charging function | Discharging function | Seal capability |
|---|---|---|---|
| 0 | Good | Good | OK |
| 10 | Good | Good | OK |
| 20 | Good | Good | OK |
| 30 | Good | Good | OK |
| 40 | Good | Good | OK |
| 50 | Good | Good | OK |
| 60 | Good | Good | OK |
| 71 | Good | Good | OK |

## 4 Expectation

Nowadays, material science is developing rapidly, and many new materials appear continually. Following the development of exact machining and seawater hydraulic technology, the seawater-type hydraulic VB system will be widely used in manned submersible.[7]

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**QIU Zhong-liang** was born in 1979. He is an engineer at China Ship Scientific Research Center. His current research interests are research, design and exploitation of underwater machine and hydaulic system.

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Zenisu deep-sea channel originated from a volcanic arc region, Izu-Ogasawara Island Arc, and vanished in the Shikoku Basin of the Philippine Sea. According to the swath bathymetry, the deep-sea channel can be divided into three segments. They are Zenisu canyon, E-W fan channel and trough-axis channel. A lot of volcanic detritus were deposited in the Zenisu Trough via the deep-sea channel because it originated from volcanic arc settings. On the basis of the swath bathymetry, submersible and seismic reflection data, the deposits are characterized by turbidite and debrite deposits as those in the other major deep-sea channels. Erosion or few sediments were observed in the Zenisu canyon, whereas a lot of turbidites and debrites occurred in the E-W channel and trough axis channel. Cold seep communities, active fault and fluid flow were discovered along the lower slope of the Zenisu Ridge. Vertical sedimentary sequences in the Zenisu Trough consist of the four post-rift sequence units of the Shikoku Basin, among which Units A and B are two turbidite units. The development of Zenisu canyon is controlled by the N-S shear fault, the E-W fan channel is related to the E-W shear fault, and the trough-axis channel is related to the subsidence of central basin.

4.外文期刊 Sakamoto Izumi Sedimentary processes and development of the Zenisu deep-sea channel, Philippine Sea

Zenisu deep-sea channel originated from a volcanic arc region, Izu-Ogasawara Island Arc, and vanished in the Shikoku Basin of the Philippine Sea. According to the swath bathymetry, the deep-sea channel can be divided into three segments. They are Zenisu canyon, E-W fan channel and trough-axis channel. A lot of volcanic detritus were deposited in the Zenisu Trough via the deep-sea channel because it originated from volcanic arc settings. On the basis of the swath bathymetry, submersible and seismic reflection data, the deposits are characterized by turbidite and debrite deposits as those in the other major deep-sea channels. Erosion or few sediments were observed in the Zenisu canyon, whereas a lot of turbidites and debrites occurred in the E-W channel and trough axis channel. Cold seep communities, active fault and fluid flow were discovered along the lower slope of the Zenisu Ridge. Vertical sedimentary sequences in the Zenisu Trough consist of the four post-rift sequence units of the Shikoku Basin, among which Units A and B are two turbidite units. The development of Zenisu canyon is controlled by the N-S shear fault, the E-W fan channel is related to the E-W shear fault, and the trough-axis channel is related to the subsidence of central basin.

5.外文会议 Liu Tao The application of deep-sea vehicles in the 21~(st) century

The deep-sea vehicle is a kind of equipment, which can carry all sorts of electronic and mechanical devices, engineers and scientists to severe deep sea environment rapidly and accurately, and can perform ocean exploring, scientific survey and operational missions more effectively. The vehicle is an important technical tool for human to perform ocean-exploring tasks.

6.期刊论文 YU Jian-cheng.ZHANG Ai-qun.WANG Xiao-hui.WU Bao-ju Adaptive Neural Network Control with Control Allocation for A Manned Submersible in Deep Sea -中国海洋工程（英文版）2007,21(1)

This paper thoroughly studies a control system with control allocation for a manned submersible in deep sea being developed in China. The proposed control system consists of a neural-network-based direct adaptive controller and a dynamic control allocation module. A control energy cost function is used as the optimization criteria of the control allocation module, and weighted pseudo-inverse is used to find the solution of the control allocation problem. In the presence of bounded unknown disturbance and neural networks approximation error, stability of the closed-loop control system of manned submersible is proved with Lyaponov theory. The feasibility and validity of the proposed control system is further verified through experiments conducted on a semi-physical simulation platform for the manned submersible in deep sea.

7.期刊论文 张宁 浅论我国深海载人潜水器的发展趋势及管理体制 -海洋开发与管理2008,25(8)

海洋是地球上尚未被人类充分认识和开发利用的各种自然资源潜在的战略基地,因此历来受到各世界强国的关注.分析了目前世界上深海载人潜水器的发展情况及其运行和管理体制,探索了我国深海载人潜水器的发展的管理模式与运行体制,对今后发展我国载人潜水器事业和海洋开发事业有一定的借鉴意义.

8.期刊论文 汤国伟.邱中梁.王璇.TANG Guo-wei.QIU Zhong-liang.WANG Xuan 深海载人潜水器压载水箱注排水系统研究 -液压与气动2008,""(3)

介绍了深海载人潜水器压载水箱注排水系统的历史发展,分析了世界上深海载人潜水器中典型的几种压载水箱注排水系统的特点,并提出了系统的设计难点和相应的解决措施,最后展望了将来压载水箱注排水系统的发展趋势.

9.期刊论文 汤国伟.邱中梁.高波.TANG Guo-wei.QIU Zhong-liang.GAO Bo 深海载人潜水器纵倾调节系统设计研究 -液压与气动2007,""(4)

介绍了深海载人潜水器纵倾调节系统设计的思路,分析了目前世界上现有的几台深海载人潜水器纵倾调节系统设计的特点,展望了深海载人潜水器纵倾调节系统将来的发展趋势.

10.期刊论文 黄建城.胡勇.冷建兴.HUANG Jian-cheng.HU Yong.LENG Jian-xing 深海载人潜水器载体框架结构设计与强度分析 -中国造船2007,48(2)

载体框架是用于安装固定载人舱、蓄电池、可弃压载、可调压载水舱、高压气罐和浮力块等深海载人潜水器设备的空间桁架结构,也是深海载人潜水器布放、回收和甲板系固的主要承力结构.因此,载体框架的设计应便于设备、仪器、浮力块和轻外壳的安装、拆卸与维护;并有足够的强度和刚度,以保证载人潜水器的布放和回收,以及在母船甲板上系固.在上述条件下,还应使其重量尽可能小.总结和介绍了我国正在建造的深海载人潜水器载体框架的材料选择、计算工况及设计载荷与许用应力的确定、结构型式的确定、构件的连接方式、节点的优化处理,以及结构强度的分析方法,给出了载体框架在单点回收和甲板系固两种工况下的强度分析结果,为今后研制同类型产品提供参考.