Researching on mathematical computation and experimental bench design of high-pressure blowing system

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Abstract. Utilized in sinking and surfacing of Autonomous Underwater Vehicle(AUV), the high-pressure blowing system(HPBS) had played an important role in maneuvering pilot of AUV and must be investigated thoroughly, by which the reserve buoyancy can be controlled. Because of the costliness of experiment on the real ship, an experimental bench of HPBS had been proposed and designed. After mathematical computations of sinking and surfacing processes of AUV, the pressure vessel prototype and it critical physical parameters selection were accomplished, which were used as ballast tank and sea environmental tank of the HPBS experimental bench. Based on those, the blueprint of the total experimental bench had been drawn and the working course of HPBS had been demonstrated.

1. Introduction

Autonomous underwater vehicle (AUV for short), which had been manufactured to accomplish many underwater tasks, including environment explorations of the sea environment[1], seabed-structure survey[2], marine ecology researches[3], ocean scenery filming[4], underwater rescuing military uses[5][6] and etc. With the increasing complexity of missions, the underwater survive-ability and endurance had become more and more important[7].

The high-pressure blowing system(HPBS) of an Autonomous Underwater Vehicle(AUV), is used to sustain the survival of the boat in the ocean and composed of several ballast tanks along its two shipboard. The tanks are used to control the reserve buoyancy and equipped with high-pressure air blowing apparatus and vent valves on its top, and sea valve on its bottom.

For AUV or manned submarines, a precise hovering system will be an effective apparatus[8], which can be applied for a delivery of swimmers, deep-sea rescuing, which had become a favorite topic recently [9]. However, the hovering system was utilized to keep a constant depth during the operations above, its reserving buoyancy is not enough for the manipulations of surfacing and diving of AUV. So a set of HPBS is still available[10].

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When surfacing, the tanks are blown and water inside is expelled into the ocean through the sea valve. When sinking, the air will be exhaust into the atmosphere or sea through the vent valve and seawater outside the tank will flood in through the sea valve. In navigation, when all the tanks filling with water, the AUV will dive. On the contrary, when water in the tank was blown the boat will levitate [11]. It can be inferred that the tactical performance of the AUV is greatly influenced by the HPBS.

During surfacing, if the friction and pressure loss is omitted, the whole processing can be regarded as a Laval nozzle operation, in which the channel diameter will be reduced at first and expanded later. In addition, the high-pressure air blowing through a Laval nozzle can be regarded as an exponential or isentropic model. If the former had been chosen, the key point is to select the appropriate blowing constant based on a previously known blowing mass and flow rate, just to satisfy with the time response [12][13]. However, the high-pressure air blowing will be operated under different back-pressure and various mass flowing rates. So the isentropic model will be more appropriate[14].

In maneuvering computation of AUV, the blowing process will be regarded as a force or moment in the 6-DOF motion equations, and blowing and flooding of the ballast tanks should be accomplished by volume transformation method(VOF)[8].When blowing, the water in the ballast tanks is expelled out by the expanding high-pressure air inside the tank, draining into the sea. To illustrate this operation, two mathematical models can be adopted, including volume transformation method and Bernoulli equations [15]. In the former, the expelling bulk of water will be computed based on specific pitching, depths and coordinates of each tank of the AUV, even the diameter of the its hull should be considered, so it will be more suitable for real ship construction design[16]. In the latter, it is supposed that the cross-section area of the ballast tank was larger than the flowing area of the sea valve, and the water drained in an even flowing mass rate, which depends on the coefficient of the flowing mass rate, the flowing aperture area of the sea valve and the pressure difference on its two sides[17]. According to the designing requirements of the experimental bench, the latter will make much more senses.

During sinking, the ballast tank will be flooded. The flooding process is similar with the draining of surfacing, and the Bernoulli equation will be used again. The flooding mass rate is concerned with the current depth of AUV, the air pressure difference of the sea valve and current liquid level of the tank, the cross section area and coefficient of the flowing mass rate of the sea valve[18].When flooding, the vent valve will be open and the air will be exhausted. The whole process was similar with the high-pressure blowing in a supersonic speed, in which the pressure difference was much smaller and can be considered as adiabatic. The exhausting rate on the top of the ballast tank was concerned with the exhausting aperture area, the pressures inside and outside of the vent valve [19].

According to the physical experiments of the processes above, two approaches can be adopted. Firstly, performances test on the real ship, which will cost much in both human resources and outlay. Secondly, an experimental bench, which will be of the fixed scale ratio to the real ship and designed in the same mathematical principle[20]. In this way, perhaps there will be data errors between the experiment and real ship performances, but it will make great senses in mathematical calculations, new prototype developing and budget control.

The total schematic of the experimental bench can be seen in Fig1. Firstly, the ballast tank inside the sea environmental tank was cylindrical. Secondly, the blowing and vent valves were both fixed on top of the ballast tank, while the back pressure and safety valves were set on top of the sea environmental tank, so as to simulate the ocean environment with a certain depth. Thirdly, water in the
ballast tank can be expelled out through the sea valve; it can also be flooded when the vent valve was open.

2. Mathematical model design

2.1 Blowing and pumping

2.1.1 Blowing process. Inside the ballast tank, the air pressure defined as \( p_B \), the air volume defined as \( V_B \), the initial volume defined as \( V_{B0} \), which equals 0.001 m\(^3\), the air mass inside the tank defined as \( m_B \), the air constant defined as \( R = 287.1 \, J/kg \cdot K \), temperature defined as \( T_B = 298K \). So the relations between them can be seen as below:

\[
P_B V_B = m_B RT_B
\] (1)

After derivative calculation of equation(1), we will get:

\[
\frac{dP_B}{dt} = \frac{dm_B}{dt} \frac{RT_B}{V_B} - p_B q_B
\] (2)

Where, \( \frac{dm_B}{dt} = \dot{m}_B = -\dot{m}_F \) was used to represent the air mass blowing rate of ballast tank, \( \dot{m}_F \) was defined as the air mass blowing rate of air bottles, \( q_B = \dot{V}_B = \frac{dV_B}{dt} \) was defined as the high-pressure air volume blowing rate. And the air mass blowing rate of the ballast tank \( \dot{m}_B \) can be calculated as below:

Fig.1 Draft of high-pressure blowing experimental bench
When \( \frac{P_B}{P_F} \geq \left( \frac{2}{k+1} \right)^{\frac{k}{k-1}} \),

\[
\dot{m}_B = -\dot{m}_F = \frac{C_A P_F}{\sqrt{R T_F}} \sqrt{\frac{2k}{k-1}} \left[ \left( \frac{P_B}{P_F} \right)^{\frac{2}{k}} - \left( \frac{P_B}{P_F} \right)^{\frac{k+1}{k}} \right]
\]

When \( \frac{P_B}{P_F} \leq \left( \frac{2}{k+1} \right)^{\frac{k}{k-1}} \),

\[
\dot{m}_B = -\dot{m}_F = \frac{C_A P_F}{\sqrt{R T_F}} \sqrt{k} \left( \frac{2}{k+1} \right)^{\frac{k}{k-1}}
\]

In equations (3) and (4), \( k \) defined as the adiabatic index, which equals 1.4, \( P_F \) was the pressure of the high-pressure air bottle, which equals 25 MPa, \( T_F \) was the temperature of the high-pressure air bottle, whose initial temperature \( T_{F_0} \) was 298 K. \( A \) was the flowing-area of high-pressure air bottle, whose diameter was about 0.018 m. \( C \) was the flowing-rate coefficient of the air bottle, which equals 0.7.

According to the exhausting of air bottles, it can be considered as an adiabatic process, so \( P_F \) and \( T_F \) can be calculated as below in equation (5) and (6):

\[
P_F = \left( \frac{m_F}{m_{F_0}} \right)^k P_{F_0} \quad T_F = \left( \frac{m_F}{m_{F_0}} \right)^{k-1} T_{F_0}
\]

\[
m_{F_0} = \frac{P_{F_0} V_{F_0}}{R T_{F_0}} = \frac{2500000 \cdot 0.41}{287 \cdot 298} = 119.85 \text{kg}
\]

2.1.2 Pumping process. In equation (2), \( q_B \) is the volume blowing rate of the high-pressure air inside the ballast tank, which equals the water pumping rate on bottom of the ballast tank. According to Bernoulli equations\(^{[21]} \), \( q_B \) can be calculated as below:

\[
q_B = C_h \cdot A_h \cdot \sqrt{\frac{2 (P_B - P_{SEA})}{\rho}}
\]

In equation (7), \( C_h \) defined as flowing-rate coefficient of ballast tank waterspout, which equals 0.45. \( A_h \) defined as flowing area of ballast tank waterspout, which equals 189.379 mm. The water back pressure out of the ballast tank can be calculated as below:

\[
P_{SEA} = 0.1 + \rho \cdot g \cdot (depth - x_B) \cdot \sin \left( \frac{\pi \cdot \theta}{180} \right)
\]

In equation (8), \( \rho \) defined as density of the seawater which equals 1025 kg/m\(^3\), \( g \) defined as gravity acceleration, which equals 9.8 m/s\(^2\), \( depth \) defined as current depth. \( x_B \) defined as coordinate between the ballast tank barycenter and AUV barycenter, which equals 0 in the physical bench. \( \theta \) defined as trim angle of the AUV, which equals 0 in the physical bench.
2.2 Flooding and ventilation

2.2.1 Flooding process. According to Bernoulli equations, the flooding rate of the ballast tank $V_b$ could be calculated as below:

$$V_b = \sqrt{\frac{2}{\rho} (p_{SEA} - p_b - \rho gh)}$$

(9)

In equation(9), $p_b$ defined as air pressure inside ballast tank. When the tank is flooding, the vent valve on the top open and $p_b$ equals 0. $\rho gh$ defined as the liquid pressure generated by the instantaneous liquid level inside the ballast tank. $p_{SEA}$ defined as the back pressure out of ballast tank and could be calculated as below:

$$p_{SEA} = 0.1 + \rho \cdot g \cdot (\text{depth} - x_b \cdot \sin\left(\pi \cdot \frac{\theta}{180}\right))$$

(10)

Where, $\rho$ defined as density of seawater, which equals 1025 kg/m$^3$. $g$ defined as gravity acceleration and equals 9.8 m/s$^2$. depth defined as the current depth. $x_b$ defined as the coordinate between the ballast tank barycenter and AUV barycenter, which equals 0 here. $\theta$ defined as the trim angle of the AUV, which equals 0 here.

The cross section area of ballast tank was defined as $A_b$ and $C_b$ as the flooding rate coefficient, $A_b$ as the flowing area of ballast tank, $V_b$ as the rising rate of the liquid level of ballast tank[12], which can be calculated as below:

$$\dot{h} = V_b = \frac{C_b A_b}{A_k} \sqrt{\frac{2}{\rho} (p_{SEA} - p_b - \rho gh)}$$

(11)

2.2.2 Ventilation process. The ventilation process was similar with exhausting of the air bottles, which had been introduced in section 2.1.1. Because of much lower pressure difference than blowing, it can be regarded as subsonic. The air mass exhausting rate could be calculated as below:

$$m_b = \frac{A_b \cdot p_b}{R \cdot T_b} \sqrt{\frac{2k}{k-1} \left[ \left( \frac{p_a}{p_b} \right)^\frac{k}{k-1} - \left( \frac{p_a}{p_b} \right)^\frac{1}{k} \right]}$$

(12)

In equation(12), $A_b$ defined as the flowing area of the vent valve, $p_b$ defined as the air pressure inside the ballast tank; $R$ defined as the air constant and $R = 287.1 J/kg \cdot K$; $k$ defined as the adiabatic index, which equals 1.4; the temperature $T_b = 298K$; $p_a$ defined as the atmosphere pressure, which equals 0.1 MPa; $h$ defined as the liquid level and $V_b$ defined as the volume of the ballast tank. The whole process was adiabatic, and could be calculated as below:

$$\left( \frac{p_{b0}}{p_b} \right)^\frac{k}{k-1} = \frac{T_{b0}}{T_b}$$

(13)

$$p_b = \left( \frac{m_b RT_{b0}}{V_{A} - A_{b} \cdot \dot{h}} \right)^\frac{k}{k-1} \cdot \left( \frac{1}{p_{b0}} \right)^\frac{k-1}{k}$$

(14)

In equation(13) and(14), $p_{b0}$ and $T_{b0}$ defined as the initial pressure and temperature of the ballast tank before water flooding.
2.3 Disturbance from the ambient physical environment

All the computations above had been accomplished in condition that the external physical environment was ideal. However, the ambient environmental disturbance must be considered.

As far as the AUV is concerned, it will be surfacing during the high-pressure blowing, so the back pressure in the sea tank will be decreased as the boat levitate. It is supposed that the AUV surface at the rate of 2 m/s, so that the back pressure $p_{SEA}$ could be calculated as below:

$$p_{SEA} = 0.1 \cdot \rho \cdot g \cdot (depth - x_0) \cdot \sin \left( \frac{\pi \cdot \theta}{180} \right) - 2 \cdot t$$

(15)

2.4 Computations

2.4.1 Permanent back pressure. The mathematical computation of high-pressure blowing in permanent back pressure had been operated in Matlab, and the critical physical parameters can be calculated, including the air pressure $P_B$, the air volume $V_B$ inside the ballast tank, the pressure difference on the wall of ballast tank which was defined as $P_B - Ph$, the air pressure of the sea environmental tank top $PJ$. In addition, it was supposed that the back pressure outside the ballast tank was 5 MPa.

All the parameters had been mentioned above can be seen in Fig2-Fig5.

![Fig2](image1)

Fig2 the air pressure $P_B$ inside the ballast tank (MPa)

![Fig3](image2)

Fig3 the air volume $V_B$ inside the ballast tank ($m^3$)

![Fig4](image3)

Fig4 the air pressure difference of the ballast tank $P_B - Ph$ (MPa)
2.4.2 Variable back pressure. The mathematical computation of the high-pressure blowing in variable back pressure had been operated in Matlab, and the critical physical parameters can be calculated, including the air pressure $P_B$ inside the ballast tank, the air volume $V_B$ inside the ballast tank, the pressure difference on the wall of ballast tank, which is defined as $P_B - P_h$, the air pressure of the sea environmental tank top $P_J$. In addition, it was supposed that the initial back pressure outside the ballast tank is defined as $5 \text{ MPa}$ and it will be decreased with the elevation of the AUV.

All the parameters had been mentioned above can be seen in Fig6-Fig9.

Fig5 the air pressure of the sea environmental tank top $P_J$ (MPa)

Fig6 the air pressure $P_B$ inside the ballast tank (MPa)

Fig7 the air volume $V_B$ inside the ballast tank ($m^3$)
3. Physical experimental bench design

3.1 Critical physical parameters
From those data above, the basic parameters of the ballast and sea environmental tanks can be determined, including the regulated air pressure, the air volume and pressure difference of the ballast tank, and the air pressure of the sea environmental tank top.

(1) The air pressure inside the ballast tank $P_B$

In Fig2, the peak air pressure of the ballast tank $P_B$ had reached $5.8 \ Mpa$, and returned to $4.8 \ Mpa$ soon, which went on continuously.

In Fig6, the peak air pressure of the ballast tank $P_B$ had reached almost $5.8 \ Mpa$, the water inside the tank had been blown out and the AUV surface. When the boat raises to the sea surface, $P_B$ had attenuate to nearly $0 \ MPa$.

To guarantee the safety of ballast tank, the working pressure of the vessel should be $10 \ MPa$, nearly two times of the peak.

(2) The volume of the ballast tank $V_B$

In Fig3, the maximal volume of the high-pressure air $V_B$ had been expanded to $1.4 \ m^3$, so that the volume of ballast tank should be smaller. In Fig7, because of the surfacing of the AUV, the back pressure decreases and high-pressure air expands out of the ballast tank, so the air volume $V_B$ increases continuously. To guarantee the evacuation of the ballast tank during operation, the maximal volume of the vessel should be $1.3 \ m^3$, smaller than $1.4 \ m^3$.

(3) The pressure difference on the wall of ballast tank $P_B - Ph$

In Fig4, the air pressure difference on the wall of ballast tank had reached nearly $0.7 \ Mpa$, which means the wall thickness should bear more than it. In Fig8, the air pressure difference on the wall of ballast tank had reached nearly $-5 \ Mpa$, which means the wall thickness should bear more than it. So the wall tightness of the ballast tank had been set to $6 \ MPa$, which was a little larger than the absolute...
value of \(-5\) MPa.

(4) The air pressure of the sea environmental tank top \(P_J\)

In Fig 5, the air pressure of the sea environmental tank top had risen to 6.3-6.35 MPa for the reason of water expelled from the ballast tank by expansion air, then it returned to 5.1 MPa and went on in constant value. In Fig 9, the air pressure of the sea environmental tank top had decreased from 5 MPa to -5 MPa and kept on. Because all the water of ballast tank was expelled, the permanent pressure acting on the ballast tank wall came into being.

So that, the regulated working pressure of the sea environmental tank should be set as 5 MPa.

3.2 Physical experimental bench design

In the experimental bench design, construction of an internal ballast tank with the sea environmental tank around was the core. Top of the ballast tank was equipped with ventilation and blowing valves; its bottom was weld with sea valve. Top of sea environmental tank was weld with safety, ventilation valves and back pressure pipes, its bottom was laid with flooding and sinking holes. Upper space of the two tanks were equipped with thermometers and liquid level meters; the ventilation of two tanks will be conducted to a funnel which was used to test the flooding of the tanks. Stricture diagram of the physical experimental bench can be seen as below in Fig 10.

![Diagram of experimental bench](image)

Fig 10 the structure diagram of high-pressure blowing experimental bench
3.3 Pressure vessel prototypes
Based on the data above, the main performance parameters of the ballast and sea environmental tank can be seen as below in Tab1 and Tab2. All the parameters were reckoned under occupation standard of pressure vessels.

**Tab1** Performance parameters of the ballast tank

| Parameters                  | Designed value | Function demonstration                                      |
|-----------------------------|----------------|------------------------------------------------------------|
| Regulated Working pressure  | 10.0 Mpa       | The maximal working pressure                               |
| Designed working pressure   | 12.5 Mpa       | The working pressure determined by the thickness of the tank and printed on the nameplate of the vessel. When the tank was equipped with safety apparatus, it will be 1.25 times of the regulated working pressure |
| Air test pressure           | 11.5 Mpa       | 1.15 times of the regulated working pressure               |
| Hydraulic test pressure     | 12.5 Mpa       | 1.25 times of the regulated working pressure               |
| Air tightness test pressure  | 10.0 Mpa       | 1.00 times of the regulated working pressure               |
| Safety apparatus            | 10.0 Mpa       | Cracking pressure, at which the valve clack will rise and the air discharges |
| Water flowing aperture      | 189.379 mm     | The equivalent flowing aperture of the sea valve on the bottom of the ballast tank, The details of the reckoning will be figured in Appendix A, Formula(A.1). |
| Effective volume            | 1.3 m$^3$      | Tenth of volume of the sea environmental tank              |
| Working temperature         | ≤50°C          | The environmental temperature of the medium                |

**Tab2** Performance parameters of the sea environmental tank

| Parameters                  | Designed value | Function demonstration                                      |
|-----------------------------|----------------|------------------------------------------------------------|
| Regulated Working pressure  | 5.0 Mpa        | The maximal working pressure                               |
| Designed working pressure   | 6.25 Mpa       | The working pressure determined by the thickness of the tank and printed on the nameplate of the vessel. When the tank was equipped with safety apparatus, it will be 1.25 times of the regulated working pressure |
| Air test pressure           | 5.75 m$^3$ Mpa | 1.15 times of the regulated working pressure               |
| Hydraulic test pressure     | 6.25 Mpa       | 1.25 times of the regulated working pressure               |
| Air tightness test pressure  | 5.0 Mpa        | 1.00 times of the regulated working pressure               |
| Safety valve prototype      | 5.0 Mpa        | Cracking pressure on which the air inside the tank will be released. |
| Effective volume            | 13 m$^3$       | Ten times of volume of the ballast tank                    |
| Working temperature         | ≤50°C          | The environmental temperature of the medium                |

3.4 Working processes
The working condition of the experimental bench is listed as below:

(1)The back pressure of the sea environmental tank outside the ballast tank is 5 Mpa, the air constant $R = 287.1 \text{J/kg} \cdot \text{K}$, the current temperature of the tank $T_b = 298 \text{K}$, which means 25 °C, the current density of water is $1025 \text{kg/m}^3$, the gravity acceleration is $9.8 \text{m/s}^2$;
(2) Now it is assumed that the height of the ballast tank is 1.53 m, whose diameter is 1 m; The height of the sea environmental tank is 4 m, whose diameter is 2 m; the sea valve diameter of the ballast tank is 189.379 mm, and its flowing coefficient is 0.45;

(3) The volume of the air bottle is 410 L, and its internal air pressure is 25 MPa.

At the time of 20 s, the high-pressure air from the air bottles exhausted into the tank in a supersonic speed, the expansion air zone in the ballast tank was signed in while.

A certain bulk of water of the ballast tank was expelled to the sea environmental tank, the expansion water zone in the sea environmental tank was labeled in light blue with its height defined as \( h \). What is more, the flowing direction of the whole process was labeled in arrows in Fig11.

![Fig11 the working process of high-pressure blowing](image)

4. Conclusions

The performance of the high-pressure blowing of based on AUV ballast tank had been investigated using mathematical computation and the experimental bench had been designed. Simulations were demonstrated that the HPBS could be used to accomplish the mathematical calculation of high-pressure blowing and experimental tests.

The high-pressure blowing and water-flooding operations of the ballast tank were a very promising strategy to apply in AUV and other various underwater platforms. Not only the regulated maneuvering control but also the safety of the whole vehicle could be guaranteed by those actions. To make an impeccably analysis of this system, the mathematical model had been used to compute the blowing and flooding in a certain environment, and a physical experimental bench based on those had been
designed. In case of AUV vehicles, more factors of the physics reality should be considered in using the physical experimental bench, not only back pressure changing in blowing, but also the pressure loss, loud noises from mixture of water and air and etc, which will be the subject of our future work.

**Acknowledgement**

This work was supported by the fund of project of the teaching equipment construction of naval university of engineering in 2019, construction of submersible system physical experimental bench.

**Appendix A**

The criterion of scaling model computation is the constant ratio between the volume of the tank and the flowing area of the sea valve, to guarantee the physical similarities[16][17].

So, the water flowing aperture of the ballast tank will be calculated on base of permanent flowing rate between the AUV and the HPBS.

\[
\frac{V_{\text{AUV}}}{n \cdot \pi \cdot \left( \frac{R_v}{4} \right)^2} = \frac{V_{\text{bench}}}{\pi \cdot \left( \frac{R}{4} \right)^2}
\]  \hspace{1cm} (A.1)

With the volume of the AUV ballast tank \(V_{\text{AUV}}\), diameter of the sea valve plate \(R_v\), number of the sea valve plate \(n\), the flowing rate of the AUV ballast tank \(V_{\text{AUV}}/n \cdot \pi \cdot \left( \frac{R_v}{4} \right)^2\); the equivalent volume of high-pressure blowing experimental apparatus \(V_{\text{bench}}\) and its water flowing aperture of the ballast tank \(R\), the flowing rate of the experimental apparatus equals \(V_{\text{bench}}/\pi \cdot \left( \frac{R}{4} \right)^2\).

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