3D Numerical Simulation of Expendable Bathythermograph Probe Dropping

Wenlong Lv, Yongjie Wang and Fang Li

1 State Key Laboratories of Transducer Technology, Institute of Semiconductors, Beijing, China
2 College of Materials Science and Opto-Electronic Technology, University of Chinese Academy of Sciences, Beijing, China
E-mail: lw1@semi.ac.cn

Abstract. In order to study the motion of Expendable Bathythermograph (XBT) probe, the transient dropping process is numerically simulated by using Fluent software. In the paper, the dynamic mesh method, the 6DOF solver and the volume of fluid (VOF) model are used in Fluent. The trajectory, speed and rotating speed of the probe are investigated, and we also analyze the influence of the tail fin’s shape on the rotating speed. The numerical results show that the trajectory and key velocity of XBT probe are in accordance with the relevant research results. And we could get more detailed information than theory or experiment methods. The work can provide a research basis for the research on the underwater motion, stability and structure design of the XBT probe.

1. Introduction
The Expendable Bathythermograph (XBT) is a kind of instrument for measuring the temperature of seawater at different depths. There are important applications in scientific research, marine environment investigation and military purposes. It is rapid, easy and inexpensive in measuring the temperature of seawater. The XBT probe is a disposable device, it is usually released from the ship and quickly measures the temperature of seawater during navigation. Figure 1 shows the shape of XBT probe. The probe is a torpedo-shaped detector with a thermistor inside the diversion chamber, which measures seawater’s temperature when dropping in water. The data of the temperature is transmitted to an on-board data acquisition system by fine coated wire. Since it doesn’t contain pressure sensors, the depth of the XBT probe is not directly measured, but determined by the fall-rate equation (FRE) obtained by CTD calibration.

Most of the researches on XBT probe are mainly around the fall rate equations. Green (1984) firstly proposed the motion equations of XBT falling, taking into account the probe's mass, drag coefficient, wire loss, etc. Later, some scholars started using the CFD methods to study the flow state and motion state of XBT in water; In order to obtain the drag coefficient, Abraham (2012) numerically simulated the XBT probe rotating at a certain speed by CFX software; Hong Xiao (2012) simulated the falling process of XBT probe with the VOF method. Early numerical simulations on XBT were mainly steady flow analysis, which were based on the quasi-steady state assumption of flow field. Few people have numerically simulated the whole sinking process of the probe and analyzed the rotation. This paper not only simulates the dynamic process of XBT probe dropping, but also considers the rotation. Here, we analyze the trajectory, velocity and rotating speed with Fluent software. At the same time, the influence of the tail fin’s shape on the rotation is also analyzed.
2. Methodology

2.1. Governing equations for rigid body in motion

According to the working mechanism of XBT, we need to determine the correspondence between depth and temperature. Therefore, it is necessary to study the speed of the probe before practical application.

XBT probe is released freely in the air, because the air density is very low, the drag and buoyancy force of the probe in air can be ignored. When XBT probe hits the water, the speed reaches \( v_{ff} \):

\[
v_{ff} = \sqrt{2gh_0} \tag{1}
\]

Where \( g = 9.81 \text{ m} \cdot \text{s}^{-2} \) is the gravitational acceleration and \( h_0 \) is the drop height.

Then the momentum of probe will reduce due to the impact on water, which means the velocity of the probe is reduced to \( v_0 \) after impacting, and the velocity loss of probe in water can be obtained:

\[
\Delta v = v_{ff} - v_0 \tag{2}
\]

Finally, the probe is submerged in water, we can get the velocity \( v_{new} \) of probe at each moment according to the velocity \( v \) of the previous time step:

\[
v_{new} = v + \frac{\Delta t}{m_p} \left( (m_p - m_w)g - C_d \frac{1}{2} \rho v^2 A - v^2 \frac{dm_p}{dz} \right) \tag{3}
\]

The model is account for variations of the buoyancy force, the drag force and the mass reduction due to wire payout. The term \( m_p \) is the probe mass, \( m_w \) is the mass of the water discharged by the probe, \( C_d \) is the drag coefficient, and \( \rho \) refers to the seawater density.[5]

2.2. Governing equations for fluid

The dropping of the probe involves some interactions with water, and the basic control equations for fluid include: mass conservation equation, momentum conservation equation and energy conservation equation[6]. However, the energy conservation equation is not considered here.

2.2.1. Mass conservation equation

\[
\frac{\partial \rho}{\partial t} + \rho \text{div}(\vec{u}) = 0 \tag{4}
\]

Where the term \( \rho \) is the density of fluid, \( t \) is time, \( \text{div} \) is divergence, and \( \vec{u} \) refers to the velocity vector \[4\].

2.2.2. Navier-Stokes equation
\[
\frac{\partial (u_i)}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{1}{\rho} \frac{\partial \tau_{ij}}{\partial x_j} + f_i
\]

(5)

Where the terms \( u_i \) and \( u_j \) represent the velocity vectors. \( p \) represents the static pressure. \( f_i \) is the other momentum forcing components. \( \tau_{ij} \) is the viscous term, is shown as the following:

\[
\tau_{ij} = \mu \left( \frac{\partial (u_i)}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} \right)
\]

(6)

2.2.3. Turbulence model

The moving environment of the probe is viscous, incompressible and unsteady flow field. Here we use the realizable k-\( \varepsilon \) model. The transport equations for \( k \) (J) and \( \varepsilon \) (%) are as following:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho ku_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G_k - \rho \varepsilon
\]

(7)

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + \rho C_1 \varepsilon E - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}}
\]

(8)

\[
C_1 = \text{MAX} \left( 0.43, \frac{\eta}{\eta + 5} \right)
\]

(9)

\[
E_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)
\]

(10)

Where \( k \) is the turbulent kinetic energy, and \( \varepsilon \) is the turbulent dissipation rate. \( G_k \) represents the generation of turbulent kinetic energy due to the average velocity gradient. \( \sigma_k \) and \( \sigma_\varepsilon \) is the turbulent Prandtl numbers of the turbulent kinetic energy and its dissipation rate respectively, \( \eta = (2 E_{ij} E_{ij})^{1/2} k / \varepsilon \), \( \sigma_k=1.0, \sigma_\varepsilon=1.2, C_2=1.9 \). [6]

2.3. Boundary conditions and initial conditions

In order to ensure the full development of the flow field, we set a large cylinder as the computational domain, its length is 15.5 meters, and its diameter is set as 10 times the diameter of XBT probe. The boundary of the computational domain is shown in figure 2. The top edge of the computational domain is defined as the pressure outlet, the outlet pressure is atmospheric pressure, and the remaining boundaries and probe surface are defined as no-slip walls. Others were set default.

![Figure 2. Schematic diagram of the initial position of the XBT probe](image)
The upper part of the flow field is defined as the air, the lower part is defined as the water. At first, the XBT probe is 2 meters high above the water surface. The probe is released freely in the air. And the direction of the gravity acceleration is -Z direction.

2.4. Meshing
Based on the structure of the XBT probe, we build a simulation model by SpaceClaim software and divide it into lots of tetrahedral mesh. In order to ensure the quality of mesh, the mesh near XBT probe is encrypted. The encrypted area can move together with the XBT probe to ensure that there is no negative volume mesh. They are shown in figure 3. The total number of mesh is 4499538 after completion.

![Figure 3. Tetrahedral Mesh of the computational domain and probe](image)

2.5. Dynamic mesh update
Compared to the steady state simulation of XBT probe by some previous scholars, we make a 3-D transient simulation about the probe’s falling process, which is more realistic to show the dynamic process of falling and rotating. Here, we make use of dynamic mesh method in consideration of the mesh’s motion and deformation. Specifically, the transient simulation uses the methods of Spring Smoothing and Local Remeshing.

3. Simulation results and analysis

3.1. Moving position of XBT probe

![Figure 4. Position profile of the XBT probe at different time (contours were cut through the vertical axis of the computational domain).](image)
indicating that the simulation is successful. Moreover, the section of the probe becomes smaller and smaller, which indicates that a certain deviation occurs when the probe falls. Figure 5 shows the trajectory of the whole movement process of the probe dropping. The six degree of freedom (6DOF) solver is utilized to track the trajectory of the probe by calculating the buoyancy force and the drag force. After impacting the water, the probe gradually rotates. The trajectory is kind of like a spiral line. And Stark J had noted that the XBT probe motion in near surface layer is slow rotation with helicoidal trajectory \cite{8}. While on the whole, the trajectory is a straight line.

3.2. Vertical velocity of XBT probe

Using the 6DOF solver of Fluent, we can obtain the displacement and rotating angle of XBT probe in the X, Y and Z directions. Figure 6 is the speed of the probe in the direction of gravity, roughly corresponding to the initial movement process of the probe. The probe is freely released 2 meters above the water surface. When it hits the water at about 0.63s, it reaches the maximum speed of 6.18m/s. Then there is a loss of momentum due to the impact on water surface. At about 0.66 s, the probe is submerged in water. As a result of the fluid force, XBT probe will rotate in the water, and the falling speed tends to be stable.
Figure 6. Vertical velocity of XBT probe in numerical simulation

A similar experiment was conducted abroad in 2015 [9]. The American scholar Bringas conducted the falling test of the XBT probe in a 11.12 meters deep water tank, and captured the position of the probe at different moments by a digital camera. Table 1 compares the experiment and the simulation results. We can see that the initial speed \( v_0 \) in water and the loss of speed \( \Delta v \) are close to respectively.

| Drop height (m) | \( v_0 \) (m/s\(^{-1}\)) | \( \Delta v \) (m/s\(^{-1}\)) |
|-----------------|-----------------|--------------------|
| Numerical simulation | 2 | 6.137 | 0.123 |
| Tank experiment | 2 | 5.73±0.42 | 0.53±0.42 |

3.3. Rotating speed of XBT probe

There are three triangular tail fins at the end of the XBT probe. The tail fins are bent at a certain angle, so the lift force that is perpendicular to the probe axis generates torque on the probe. The torque makes the probe rotate at a certain speed, so as to maintain the attitude stability of XBT probe. At the same time, it is beneficial to loosen the thin copper wires connected to the launch ship.

Since the rotation of the probe in the water depends on the curved tail, the bending angle of the tail fin may also affect the effect of rotation. We conduct numerical simulations on three XBT probes with different shapes, and the bending angle of the tail fins are respectively 20°, 30° and 40°. From the simulation, we obtain the 6DOF information of the probe with time going. Due to the limitation of the computing domain, the case was only calculated about 1.4s. The change of its rotating displacement about the z-axis was specially analyzed, as shown in figure 7. It can be seen from the figure that the probe hardly rotates in the air. After entering the water at about 0.66s, the rotating displacement of probe around the z axis significantly increases, which conforms to a certain actual situation. According to the rotating angle of different probes in figure 7, the larger the bending angle of the tail fin, the higher the corresponding rotating speed. The final rotating speed of 20°, 30° and 40° probe in water is 6.4r/s, 7.8r/s and 10.4r/s, respectively.
Figure 7. Rotating angle of XBT probes with different tail fins around z axis

Figure 8. Rotating speed of the probe with the 20° tail fins

Figure 8 shows the rotating speed of the probe with the 20° tail fins within 2s, including the process of free falling in air, impacting the water, rotating and falling in water. After entering the water, the probe rotates faster and finally reaches a stable rotating speed of about 7.1 r/s, which was somewhat different from the 10 r/s observed by foreign scholars [3]. In addition, there are discontinuities in the figure, which may be related to the selection of the time step.

4. Conclusion
The falling process of the XBT probe was simulated by using the VOF model and the 6DOF solver in software Fluent. The trajectory and key velocity are close to the relevant experiments respectively. The falling trajectory of XBT probe is a straight line with slight deflection in water.

Here we use the VOF method in the Fluent software to track the XBT probe’s motion interface at different time. The curved tail fins help the probe reach a high rotating speed after entering the water and maintain the posture stability in the seawater. The larger the angle of the tail fin, the easier it is to obtain a higher rotating speed.

The numerical simulation in this paper provides a research basis for further research on the underwater motion and the attitude stability of the XBT probe, which is of great significance for improving the accuracy of temperature measurement. Due to the limitation of the computational domain, the simulation results can’t fully reflect the falling process of the probe. This process will be further studied in later work.

Acknowledgments
This project is supported by The Senior User Project of RV KEXUE (KEXUE2018G08).

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