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# Exploration of measurement principle of a three-dimensional current sensor for measuring the upwelling

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ABSTRACT

The micro upwelling and the large difference of current velocity in the three-dimensions has limited the traditional flow velocity sensors to measure the upwelling. Thus, a three-dimensional current sensor which can measure the horizontal velocity and small upwelling is introduced. Based on the theory of flow around the ball, the horizontal flow velocity is measured by the ball. Additionally, based on Kutta-Joukowski theorem, the vertical flow velocity is measured by the thin disc through the results of horizontal flow velocity measurement. Through theoretical calculation and fluid simulation, the whole structure of this three-dimensional sensor has little effect on the flow around the ball and disc. Based on the results of fluid and structural simulation, it can be known that the device can measure the velocity in the range of 0 mm/s~400 mm/s and the minimum flow velocity which can be accurately measured is about 8 mm/s; if the horizontal flow velocity is 100 mm/s, the minimum upwelling velocity which can be measured is about 0.0087 mm/s and if the horizontal flow velocity is 30 mm/s, the minimum upwelling velocity which can be measured is about 0.029 mm/s.

## 1. Introduction

Ocean current velocity including horizontal flow and vertical flow is an important parameter to study the ocean. Additionally, the vertical flow includes upwelling and downwelling. Moreover, the horizontal flow velocity of the deep sea water is below 100 mm/s, but the upwelling flow velocity is very small, only $10^{-3}$ mm/s to $10^{-1}$ mm/s (Jing, 1966; Masuzawa, 1974). Although the upwelling velocity is small, it is a key factor in the formation of the fishing ground and red tide (Sun et al., 2012; Lou, 2010). However, the upwelling velocity is generally one percent or even millionth of the horizontal flow velocity, which improves the difficulty of the measurement.

At present, there are many kinds of flow velocity measuring instruments, which have different characteristics and are applied to different flow velocity measurement. In addition, according to the principle, these flow measuring instruments can be divided into mechanical, electromagnetic, hot wire, doppler optical and acoustic, acoustic time difference and particle image velocimetry, etc. However, due to the impact of the work principle, application, accuracy, and cost price, these flow velocity measuring instruments are very difficult to measure the small vertical flow velocity in the dimensions (Lu, 2011; Song, 2001; Liu and Zhang, 2008; Lin, 2005; Wang et al., 2001; Huang, 2008; Zhai, 2008; Wei, 2009; Adrain, 2005). Now, the acoustic doppler current profiler (ADCP) which is widely used can hardly measure the vertical flow velocity, because the accuracy does not meet the requirements (Lan and Qu, 2011). Only when the vertical flow velocity is fast enough in a specific region, the ADCP can reliably measure the vertical flow velocity in this special region (Storlazzi et al., 2003).

Now, there are three methods which can obtain the relevant data of vertical flow velocity. The first one is that the upwelling and related information can be judged and extracted, according to the abnormal information of sea surface temperature, ocean color, sea surface roughness in the image which is obtained from satellite remote sensing technology (Javier and Gabriel, 2006; Uiboupin and Laanemets, 2015); the second one is that the vertical flow can be judged indirectly, according to the distributions and changes of seawater temperature, salinity, fluorescence chlorophyll a, turbidity and other features (Huang et al., 2008); the last one is that the vertical flow model is established and then the numerical simulation is carried out to calculate the vertical flow velocity (Lv et al., 2007). However, these methods are too complicated. Moreover, the flow velocity can only be speculate in a large area and can't be monitored in real time.

Because of the great difference between the horizontal flow velocity and the vertical flow velocity, it is hard to tell how fast the vertical velocity is when measuring. Thus, this paper proposes a new current velocity measurement sensor using a combined model. By measuring the flow resistance of a ball and the disc lift, the horizontal flow velocity and the vertical flow velocity can be measured separately, which can meet the requirements of small, three-dimensional, transient and deep sea, etc.

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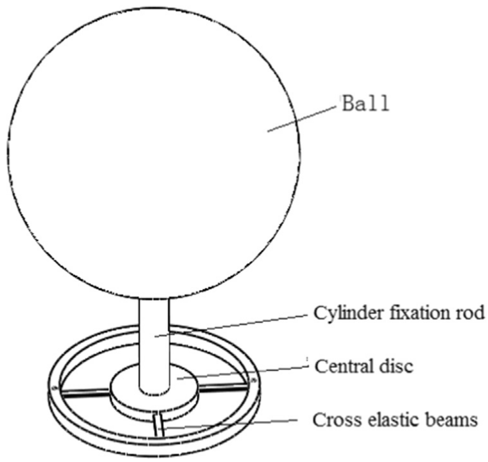


**Fig. 1.** The horizontal flow velocity measuring device.

## 2. The measurement of horizontal flow velocity

In the ocean, the horizontal flow velocity of the deep sea whose depth is greater than 200 m is below 100 mm/s. Therefore, the sensor which is applied to the deep sea should be able to measure the horizontal flow velocity of 0–100 mm/s.

### 2.1. The structure design

According to the knowledge of fluid mechanics, the velocity pressure which is produced by fluid is proportional to the square of the flow velocity. Thus, the horizontal flow velocity can be measured by measuring flow around resistance. Additionally, the parameters of horizontal flow velocity include the direction and magnitude of the velocity, which are changing in the ocean, so the structure measuring the horizontal flow velocity should be a rotating body, such as ball, cylinder or other rotating body. Finally, the hollow ball structure is chosen, in order to meet the characteristics of light weight and large vertical sectional area.

The horizontal flow velocity measuring device is shown in Fig. 1, which uses ball induction resistance to measure the horizontal flow velocity. Among of the device, the ball is connected to the central disc which is located in the center of the two vertical cross elastic beams through the cylinder fixation rod. Moreover, the ball's resistance can be transformed into moments which act on the cross elastic beams, so the direction and magnitude of horizontal flow velocity can be measured by the strain of cross elastic beams.

### 2.2. Theoretical calculation

According to the fluid mechanics, the Reynolds number can be expressed as follows:

$$\mathrm{Re}=\frac{Ud}{\nu} \tag{1}$$

Where $U$ is the velocity of sea water, $d$ is the diameter of ball and $\upsilon$ is the kinematic viscosity.

In the Eq. (1), the value of $U$ is the 20 mm/s, the value of $d$ is the 200 mm, the value of $\upsilon$ is the 0.01003 $cm^2/s$ and the value of density is the 998.2 $kg/m^3$.

The experimental data fitting formula of drag coefficient of a ball called $C_d$ can be expressed as follows (Li and He, 2006):

$$C_d = \frac{24}{\mathrm{Re}} + \frac{6}{1+\sqrt{\mathrm{Re}}} + 0.4 \quad (0 \le \mathrm{Re} \le 2 \times 10^5) \tag{2}$$

The flow resistance of a ball called $F_d$ can be expressed as follows (Li and He, 2006):

$$F_d = C_d \frac{\rho U^2}{2} s \tag{3}$$

Where $s$ is the projection area of the object perpendicular to the direction of the flow.

From Eqs. (1)–(3), the value of $F_d$ can be expressed as follows:

$$F_d = 5\pi U^2 \left( \frac{24}{199402U} + \frac{6}{1+\sqrt{199402U}} + 0.4 \right) \tag{4}$$

From the Eq. (4), it can be known that when the flow velocity is greater than or equal to 1 mm/s, it can be considered that flow resistance of a ball is proportional to the square of the velocity.

### 2.3. The simulation analysis of flow field

By analyzing the flow around resistance of a ball and resistance factor at different flow velocity, the relationships between flow velocity and the resistance of flow around the ball can be analyzed. Moreover, the formula shows that the resistance of flow around the ball is related to the diameter of ball at the same flow velocity and the larger diameter of ball is, the greater flow around resistance of a ball is. Considering the requirements of that the sensor should have small mass and small volume, the value of ball's diameter is 200 mm. Then, the outflow field can be established; afterwards, the simulation analysis of flow field for the ball can be done; finally, the changes in flow velocity and pressure near the ball can be analyzed.

(1) The setting of boundary conditions and calculation methods

The inlet boundary is set to the velocity-inlet; the outlet boundary is set to the outflow; the four sides of the fluid field are set to the velocity-inlet; the surface of ball is set to the wall, which has no wall slip.

According to the required accuracy of simulation calculations, the three-dimensional single precision and pressure based separation solver can be used for solving; when the value of inflow velocity is less than 30 mm/s, the laminar model can be selected to calculate, otherwise, the apalart-allmaras turbulence model can be used for solving; the second-order implicit scheme is used and the method of calculation adopts steady flow, the pressure-velocity coupling term uses the SIMPLEC algorithm, and the pressure dispersion uses the second-order accuracy scheme which is the second-order upwind discrete momentum equation

(2) The analysis of simulation results

In the ocean, the flow velocity of the deep sea water is generally in the 0 ~ 100 mm/s, so the flow field around the ball is simulated in the different inflow velocities within this velocity range, which can analyze the force distribution, ball resistance and ball resistance coefficient of surface of ball. The Fig. 2 shows a pressure distribution on the surface of ball and the Fig. 3 shows the pressure contour on the section Y=0. The unit of the pressure in the Figs. 2 and 3 is pascal. By observing Figs. 2 and 3, it shows that for the inflow velocity in the direction of −X, the pressure on the surface of upstream hemisphere gradually decreases from the front to the back, the pressure near the middle position is the least and the pressure on the other surface of hemisphere is gradually increasing. Besides, due to the effect of fluid viscosity, there is a loss of energy in the flow field leading to that the pressure on the surface of upstream hemisphere is greater than the pressure on the other surface of hemisphere. It can also be seen from the Figures that because of the separation of the boundary layer, the negative pressure zone is appeared at the back of the separation point and there is the reflux phenomenon in the wake field.

The Table 1 shows the flow resistance of a ball and its coefficient at different inflow velocity. Additionally, the experimental value in the Table 1 is determined by the experimental data fitting formula. The