Motion forecast of intelligent underwater sampling apparatus

—— Part I: Design and algorithm

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Received 15 July 2015; revised 30 October 2015

This paper introduces a novel intelligent underwater sampling apparatus (IUSA) mounted on autonomous underwater vehicle (AUV) with an essential practical sense, as the IUSA can be conveniently released from AUV to accomplish the underwater sampling task and then surface up by releasing the ballast itself. Mechanical design of the IUSA is briefly introduced, which has the feature of simple structure to carry the sampling sensor, low power consumption, high reliability of release and recycling utilization. It easily achieves the ability to dive in and surface up only by adjusting its buoyancy. However, it is rather difficult to confirm the surfacing time of the IUSA in order to timely recover it, since the underwater motion forecast of the IUSA is largely disturbed by complex fluid hydrodynamics. This paper presents a steady-state superposition algorithm to address the problem of motion forecast of the sampling apparatus, with the assistant of computational fluid dynamics software to take into account the dynamics of the IUSA in sea water, which is instrumental in helping the mission operators recover the apparatus for recycling utilization.

[Keywords: Autonomous underwater vehicles (AUV), Intelligent underwater sampling apparatus (IUSA), Two-level release, Motion forecast, Steady-state superposition algorithm]

Introduction

With the development of marine technology, underwater robots work as a mother ship can carry many tools used to complete a specific task. By employing an observation device carried with autonomous underwater vehicles (AUV)1, human beings can complete underwater acoustic survey2, rapid environmental assessment3, sampling and observation of biological resources4, geomorphologic mapping5, underwater pipeline inspection6, and exploration of underwater oil and natural gas7. However, due to the limitations of working depth and power capacity of underwater robots, these observation devices can be embedded in a small pressure vessel that is carried with underwater robots and can bear greater pressure. Once a special task is initiated, the pressure vessel equipped with a number of important sensors will be released by underwater robots and sink into the specified and deeper seafloor to collect related data. After finishing data acquisition, the pressure vessel should have the ability to float up to the surface. Therefore, the releasing ability at fixed time is an important function for underwater robots. Existed releasing tools mainly use the method of one-time release mostly driven by blast, which usually uses disposable and risky explosive bolts, or motor, whose structure is usually complex and having a high demand for watertight, or electromagnet8-10. In addition, one-time release is fully dependent on the mother ship that must have a high demand for
dynamic positioning and stay for a long time during working, which limits the operational capacity of the mother ship. Our overall work is to design an intelligent underwater sampling apparatus and then figure out the surfacing time and horizontal recovery range on the surface of the sea by using CFD software. This paper first introduces this novel intelligent underwater sampling apparatus by using twice release technology where the mother ship can leave after first releasing the sampling apparatus, and then propose the steady superposition algorithm for auxiliary calculation. Design of twice release technology significantly reduces energy consumption of built-in power and the apparatus also has the simple structure, high reliability of watertight and good security. Recovery at sea is achieved by searching for radio signals emitted from the antenna at the top of the apparatus. As the transmission distance of radio signal is limited, estimating the surfacing time underwater and drifting scope at sea through theoretical calculations is of great significance for recovering the apparatus.

Without equipping the propeller, rudder, electric machine and hydraulic pumps, the IUSA can dive in and surface up only by adjusting its own buoyancy. The surfacing motion of the sampling apparatus is greatly coupled with the complex fluid hydrodynamic, especially when approaching the sea surface due to environmental disturbances (i.e., wave and current) and the coupling of various flow field. Consequently, in order to accurately estimate the surfacing motion of the apparatus, this fluid hydrodynamic must be considered. Based on previous research work, a new steady-state superposition algorithm by making full use of integral method is proposed in this paper, which is able to accurately and efficiently achieve underwater movement simulation of the IUSA and take into account both of the system dynamics model and dynamic effects of sea water, by resorting to the fluid simulation software and its easy, reliable and adaptive structured grid generation technology.

Materials and Methods

Design of the IUSA

The apparatus has a two-level unit architecture including the primary release unit and the secondary release unit (Fig. 1a). The former consists of the deflector, primary releaser and primary control cabin and is installed on AUV. The latter consists of beacon, secondary releaser and ballast. Beacon includes a protective cover, antenna, secondary control module, data acquisition module and base (Fig. 1b).

![Fig.1- Intelligent underwater sampling apparatus](image)

The secondary release unit placed inside the shroud is used to lock or release the ballast. Similarly, the primary releaser is used to lock or release the connecting shaft on the top of shield. When the secondary release unit is locked by the primary releaser, the antenna on the top of beacon is compressed and the secondary control module powers off. Once the secondary release unit is released by the primary releaser, the antenna on the top of beacon will extend and then the secondary control module will power on.

The adoption of twice release technology significantly reduces energy consumption of the
built-in power. Two-stage process is respectively driven by the primary and secondary releaser, and they have the same structure and function. The like releaser is made up of the spring, detent, lever, link, armature and electromagnet (Fig.2a). When the solenoid is not energized, its natural magnet has a magnetic force to attract the armature, drive the link, and force the lever to move against the spring tension. Hence, the two detents get close head-on and then lock the suspender in the groove (Fig.2b). When the solenoid is energized, its internal anti-magnetic field generated by the coil makes it unattractive for armature. Because of the spring tension, the detents back away and then the suspender is released (Fig.2c).

According to the twice release technology, the AUV leaves immediately after releasing the apparatus and the secondary release request that has two modes, namely time-delay and timing, is mainly controlled by the secondary independent control module. The design of combining electromagnet with the lever unit can enhance the drive capability of the electromagnet. The use of a loss of power type electromagnet that releases the suspender when it powers on significantly reduces energy consumption of the built-in power. In addition, the whole apparatus can be recycled and has simple structure and high reliability of watertight thanks to the mature static sealed of electromagnet.

Workflow of the apparatus is as follows: Once the AUV reaches destination task site, the electromagnet of the primary releaser will be energized and the secondary unit will be released after the primary control cabin receives the release order from the AUV via the watertight cable. The compressed antenna popups to the trigger switch and the controller in the secondary control cabin powers on when the secondary release unit escapes from the deflector under its own gravity of 1.59Kg. After reaching the seafloor, the apparatus acquires data through data acquisition cabin. The electromagnet of the secondary releaser will be energized at the set time and then the ballast with a negative buoyancy of 3.74Kg is released. At this moment, the beacon starts to float up vertically with a positive buoyancy of 2.15Kg because the center of gravity is below the center of buoyancy. The secondary controller in the beacon urges the wireless transmitting unit to power on and then to transmit radio signals so that the mission operator could recycle the beacon through searching for the wireless signals from directional antenna.

Wind and waves on the sea is so rough that the apparatus will quickly drift with ocean currents after surfacing up. Once the device drifts away, it cannot been found due to the limitation on the transmitting distance of radio signal. Consequently, it is of great significance for apparatus recovery to figure out the surfacing time underwater and drifting displacement at sea by means of simulating the corresponding motion process through theoretical calculations.

Model of the ocean current motion

As mentioned earlier, the apparatus motioning in the ocean is bound to be influenced by the ocean currents, which are extremely complex in nature, and affected and confined by a
variety of factors. As to the apparatus movement in the ocean, the following assumption is made: the current velocity is assumed to be constant during problem analysis. As a matter of fact, it is difficult to describe the motion of ocean current with a precise mathematical expression.

Vladimir M. Kushnir explored the distribution of the current velocity along the vertical direction. According to his discovery, the velocity at depth of more than 40m is negligible, less than 0.2m/s, while the maximum value of the velocity is 1.7m/s at depth of less than 40m. Then in this paper, the ocean is divided into deep waters and shallow waters based on the separatrix characterized by the depth of 40m. For analysis simplification, the current velocity of deep waters is treated as zero, the vertical motion of the currents in shallow waters is ignored, and the average value of horizontal velocity is set as 1.7m/s. Therefore, the surfacing motion underwater of the IUSA is divided into free vertical surfacing motion and horizontal drifting motion in shallow waters with the currents moving at the velocity of 1.7m/s.

### Steady-state superposition algorithm

Based on integral thought, the steady-state superposition algorithm divides the vertical movement underwater or horizontal drifting movement in shallow waters into a number of equally spaced segments. In each segment, the apparatus does uniformly accelerated motion as a result of being in a stable state of constant fluid force. As long as the time occupied by each segment is sufficiently small, the underwater movement simulation of the apparatus will be achieved by computing fluid resistance of any segment through fluid simulation software, and deriving the beginning and final velocity of any segment through Euler forecast - Keystone numerical methods.

Whether the apparatus does the vertical surfacing motion or the horizontal drifting motion, we all divide it into a number of motion segments, where each time step is an extremely small time represented by $\Delta t$ (Fig.3). In the condition that initial velocity is zero, the velocity and displacement of the apparatus at each time will be obtained by Euler forecast - Keystone numerical integration methods.

![Fig. 3- Computing principle of stead-state superposition algorithm](image)

The specific calculation procedures are as follows:

1. Set the velocity of device at the initial time $V_0=0$, calculate the acceleration $a_0 = f(V_0)$.
2. Calculate the final velocity of device in first segment through Euler method $V_1 = V_0 + f(V_0)\Delta t$, acceleration of first segment $a_1 = f(V_1)$, and displacement of first segment $S_1 = 0.5(V_0 + V_1)\Delta t$.
3. Calculate the final velocity in second segment through Euler forecast method $V_1^+ = V_0 + 2f(V_1)\Delta t$, and then revise the velocity by Keystone formula $V_2 = V_1^+ + 0.5[f(V_1) + f(V_1^+)]\Delta t$, calculate the acceleration of second segment $a_2 = f(V_2)$ and displacement of second segment $S_2 = 0.5(V_1 + V_2)\Delta t$.
4. In common with the third step, calculate the forecast final velocity in third segment $V_2^+ = V_1^+ + 2f(V_2)\Delta t$, correction velocity $V_3 = V_2^+ + 0.5[f(V_2) + f(V_2^+)]\Delta t$, acceleration $a_3 = f(V_3)$, displacement $S_3 = 0.5(V_2 + V_3)\Delta t$.
5. And so on, the forecast final velocity in k-th segment $V_k^0 = V_{k-1}^+ + 2f(V_{k-1})\Delta t$, correction velocity, acceleration and displacement of this segment $V_k = V_{k-1}^+ + 0.5[f(V_{k-1}) + f(V_{k-1}^+)]\Delta t$, $S_k = 0.5(V_{k-1} + V_k)\Delta t$, $a_k = f(V_k)$, where $V_k^0$ is the final forecast velocity in k-th segment calculated.
through Euler forecast method, and $f(V_i^a)$ is the acceleration corresponding to the forecast velocity.

Analogously, the motion parameters including correction velocity, acceleration and displacement of each segment can be figured out so as to simulate the vertical surfacing motion and horizontal drifting motion of the apparatus, finally obtain the surfacing time and drifting scope at sea. Only unknown acceleration can be derived according to Newton’s second law after obtaining the gravity, buoyancy and fluid force bound up with profile of the apparatus, current type, relative speed between the apparatus and currents. Under certain current type, the acceleration is only related to the speed of device characterized by the equation $a = f(V_i)$, where $V_i$ represents speed of $i$-th moment, and $a_i$ represents acceleration of $i$-th moment. For this reason, the solution of fluid force at each segment is a key to realize steady-state superposition algorithm. We will calculate the fluid force through fluid simulation software in the following subsection.

**Principle of fluid force solution**

Based on thought of reverse solving and finite volume method, the fluid simulation software can computes the fluid force between apparatus and ocean current that belongs to the outflow field force.

According to the relativity of motion, the apparatus is moving at the velocity of $V_i$, which can be also regarded as that the fluid surrounding the apparatus is flowing across the static apparatus at the velocity of $V_i$ in the opposite direction but equal to $V_i$ in value (Fig.4). Therefore, the fluid force of the apparatus corresponding to certain velocity can be obtained through simulating both of the aforementioned two motions. But the former motion pattern relies on dynamic grid technology, which proposes a high computer memory requirement and cost a long time. Moreover, it does not apply to fairly complex apparatus model. Thus in the present study, the IUSA is simulated based on the second motion pattern, where the fluid force can be solved quickly by loading selected current model on the static apparatus, and based on generation technology of structured static grids.

![Fig. 4- Water flow around apparatus](image)

According to the fluid force solving flowchart of fluid simulation software (Fig.5), the governing equation should be constructed first, which is a theoretical foundation for solving any kinds of problems.

![Fig.5- Solving flowchart of fluid force](image)

The initial and boundary conditions are premises of a deterministic solution to the governing equation. Mesh generation is aimed at discretizing the governing equation. Discretization is essential not only to the spatial
domain, but also to the governing equation, the initial and boundary conditions. Only in this way can real problems be solved through computer simulation.

The continuity equation and momentum conservation equation of fluid are control equations for the fluid software to solve fluid force. In the rectangular coordinate system, the continuity equation of the steady flow of the incompressible fluid is as follows:

$$\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} = 0$$

The momentum equation of the incompressible fluid in steady conditions can be described as follows:

$$\frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_x}{\partial y^2} + \frac{\partial^2 u_x}{\partial z^2} \right) + \rho f_x = 0$$

$$\frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 u_y}{\partial x^2} + \frac{\partial^2 u_y}{\partial y^2} + \frac{\partial^2 u_y}{\partial z^2} \right) + \rho f_y = 0$$

$$\frac{\partial p}{\partial z} + \mu \left( \frac{\partial^2 u_z}{\partial x^2} + \frac{\partial^2 u_z}{\partial y^2} + \frac{\partial^2 u_z}{\partial z^2} \right) + \rho f_z = 0$$

Where $u_x$, $u_y$, and $u_z$ is the velocity component of fluid finite volume element in the direction of $x$ axis, $y$ axis and $z$ axis, respectively, $p$ is pressure on finite volume element, $\mu$ is viscous coefficient, $\rho$ is the density of seawater, and $f_x$, $f_y$, and $f_z$ is the corresponding volume force acting on the volume element in the direction of $x$ axis, $y$ axis and $z$ axis, respectively.

The basic idea of the finite volume method is to divide the calculation area into a series of non-repetitive control volumes, make the periphery of every grid have a control volume, then integrate the differential equation to be solved on every control volume, finally obtain a group of discretized equations. The following task is to solve those discretized equations. Generally, the solution method can be classified into two kinds: separation method and coupling solution. The former is to solve the variables in order rather than to solve the simultaneous equations of each governing equation directly, which is mainly applicable to low velocity field. As to the latter, each governing equation will be solved simultaneously, and variables will be obtained at the same time, which is mainly applicable to high velocity field with strong mutual dependence among the density, impetus and energy. Because the velocity of apparatus moving in the seawater is not fast enough, and only belongs to the field of low speed, the separation method is adopted in this paper to solve discretized equations. The most widely used method among separation methods is the method of pressure correction, of which the basic solving processes are as follows:

1. Assume an initial pressure field.
2. Solve the momentum equation by using the pressure field so as to obtain the velocity field.
3. Solve the continuity equations based on the aforementioned velocity field to revise the pressure field.
4. Solve the turbulence and other scalar equations according to need.
5. Determine whether the calculation at the current time step is convergent or not. If not, go back to the second step and iterate the calculation; if convergent, continue to calculate the physical quantities at the following time step with the above process being repeated.

Results and Discussion

Prototype for sampling apparatus

After this intelligent underwater sampling apparatus is manufactured, it has been tested many times in the towing tank of the Huazhong University of Science and Technology, an official member of the International Towing Tank Conference (ITTC). The tank has a length, width and height of 175 m, 6 m and 4 m, respectively.

When the IUSA is ready for work (Fig.6a), the operator uses a computer as a substitute for AUV to send the control instruction. At this moment, the secondary unit is separated from primary release unit and dive into the bottom of the water tank. After it completes sampling task through data acquisition cabin, electromagnet of
secondary releaser will be energized at the set time and then the ballast will be released, finally the beacon unit starts to float up vertically because the center of gravity is below the center of buoyancy and reaches up to the water surface (Fig.6b). The inner controller launches the wireless device in the cabin to transmit radio signals so that the mission operator could recover the beacon through searching for the signals from the directional antenna.

![Fig. 6 - The IUSA in the water](image)

**Single step solution of motion force**

As mentioned in the preceding section, the solution of fluid force at each segment is a key to realize steady-state superposition algorithm and fluid force can be calculated through fluid simulation software. On account of the previous work that SolidWorks was used in machine design of sampling apparatus, we first use SolidWorks to calculate the fluid force of the apparatus moving at certain speed in this paper. The flow simulation, one plug-in of SolidWorks software, can analyze the flow of ten types of different fluid i.e., liquid, gas/steam, real gas, non-Newton liquid and compressible liquid. It avoids the complexity of computational fluid dynamics so that the user can easily and rapidly simulate the fluid flow, and heat transfer and fluid force, which are vital to the propelling performance, simulate the fluid flow in real conditions, run “assumed” cases, and obtain the influence of fluid flow, heat transfer and fluid force on the immersed or surrounding components. As to the flow analysis by utilizing SolidWorks, we should first insert the assembly model to be analyzed, then open SolidWorks flow simulation module to build new analytical guide and complete relevant parameter setting in the guide (Table 1).

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Parameter value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis type</td>
<td>External flow</td>
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<tr>
<td>Pressure, temperature</td>
<td>Standard</td>
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<tr>
<td>Project fluid</td>
<td>water</td>
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<tr>
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<tr>
<td>Computational domain</td>
<td>Large enough</td>
</tr>
<tr>
<td>Velocity</td>
<td>External setting</td>
</tr>
</tbody>
</table>

Subsequently, the boundary conditions of the fluid analysis including setting the computational domain and fluid sub-domain are set before simulation run. In addition, the object function should be determined to achieve simulation analysis purposefully. In this paper, the resultant fluid resistance vertical to the apparatus outside surface, namely the fluid resistance at the vertical direction, is chosen as the object function.

The static pressure distribution on the apparatus and flow pressure distribution outside the apparatus at a certain time at the submerging velocity of 1m/s are related (Fig.7a, Fig.7b) and they are also related when the apparatus floats up at the velocity of 1m/s (Fig.7c, Fig.7d). The green region outside the apparatus denotes fluid sub-domain with a static pressure of 101325Pa (Fig.7b, Fig.7d). It can be observed that the range of the fluid sub-domain is large, and the incident flow surface of the submerging and surfacing apparatus are both located at one third of the length direction of the fluid sub-domain. During the diving process, the maximum static fluid pressure appears on the incident flow surface between the apparatus and sea-water, namely the tapered surface on the ballast bottom, and wide
range of negative pressure distribution, lower than static pressure of fluid sub-domain, appears (Fig.7a, Fig.7b). This is because the flow would pass the gap existing between the upper surface of the ballast and the lower surface of the apparatus when fluid flows around the ballast. In addition, the influence of cross flow will decrease with the coordinate along Y direction of the apparatus hence the static pressure of the top part of the apparatus is closest to the static pressure of the fluid sub-domain. Similarly, the static pressure on the groove surface at the upper end of the apparatus and the lower surface of the slot reaches a maximum during the surfacing process (Fig.7c, Fig.7d). As no gap exists, the range of negative pressure distribution during surfacing process is relatively small after cross flow after the fluid following across the apparatus upper surface and the static pressure at the bottom of the apparatus is closest to the fluid static pressure.

![Fig.7- Static & flow pressure distribution via SolidWorks simulation](image)

The aforementioned process is just a simple process to solve the fluid resistance according to a certain velocity, thus the above process should be repeated before the resultant force of the apparatus reaches an equilibrium status. Therefore, with the assistant of simulation software, i.e., SolidWorks, the motion forecast of IUSA based on the steady-state superposition can be accomplished.

**Conclusions**

This paper presents a novel intelligent underwater sampling apparatus with simple structure, high reliability of watertight and special function of twice release that improve the utilization of built-in energy. This apparatus dives in and floats up only by adjusting its buoyancy, and a dedicated algorithm called steady-state superposition is proposed to predict its surfacing motion so as to help the mission operators recover it in broad sea area.

At the present, the function of the designed apparatus has been tested in the water tank. By adopting the steady-state superposition algorithm, the fluid effect at certain speed has also been preliminary calculated in SolidWorks software. Next, the implementation of motion forecast based on the steady-state superposition will be done with other professional fluid simulation software, and the intelligent underwater sampling system will be tested and verified in the lakes or coastal waters.

**Acknowledgments**

This work was partially supported by National Natural Science Foundation (NNSF) of China [under Grant 51209100 and Grant 51579111], Natural Science Foundation of Hubei Province [under Grant 2014CFB253], the Specialised Research Fund for the Doctoral Program of Higher Education [under Grant 20120142120045] and the Fundamental Research Funds for the Central Universities [under Grant HUST:2015TS006].

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