On Propulsion-based Estimation of Incoming Flow Velocity

V V Kostenko¹, A Yu Tolstonogov¹

¹Institute for Marine Technology Problems FEB RAS, 5a Sukhanova Street, Vladivostok 690091, Russia

E-mail: tolstonogov.anton@gmail.com

Abstract. AUV’s actuators systems are highly affected by external conditions such as incoming flow velocity. The paper aims to estimation of incoming flow velocity based on quasi-steady model of thruster. The work motivation is compensation of incoming flow effect on AUV’s actuators dynamic model for improving actuator control or a velocity estimation in case of velocity sensors absence. The equation for incoming flow velocity estimation is presented. It accounts orientation of thrusters relative to the longitudinal vehicle axis. Thruster parameters identification procedure based on bollard pull tests and marine trials are presented. Comparative results of propulsion-based velocity estimation with DVL data are discussed. Velocity estimation error between methods is less than 0.1 m/s in steady motion and less than 0.2 m/s in transition process.

1. Introduction

Autonomous underwater vehicles attract increasing scientific attention for their agile, long-range operation and great human-labor efficiency. Their scope of application crosses various fields, including environmental monitoring, search and rescue, surveillance and security, scientific research, and public education [1, 2]. AUVs velocity and position control systems are subject to an increased focus for performance and safety. So far, most of the focus has been directed towards the design of the control system, that is, speed and positioning control systems. In contrast, the design of the actuators’ systems (thrusters and rudders dynamic models) has received less attention. However, actuators systems are highly affected by external conditions such as incoming flow velocity. For example, the efficiency of tunnel (or through-body) thrusters is exponentially dropped with incoming flow velocity increased [3]. Lift force generated by AUVs rudders is entirely provided by the exact value of incoming flow velocity. The ground velocity obtained by DVL in case of strong tidal or ocean currents may create a misconception about actuators’ models, leading to wrong motion control signals. But additional devices for measuring incoming flow (or AUV velocity relative to water, what is the same) are sometimes difficult to install. For most cases, using build-in AUV equipment is the preferred way to implement an additional function.

This paper aims to an estimation of incoming flow velocity based on the quasi-steady thruster's model. The motivation for the work is the compensation of incoming flow effect on AUV's actuators dynamic model for improving actuator control or a velocity estimation in case of axial velocity sensors absence.

There are different devices and ways for AUV velocity measuring relative to the sea bottom or water column. The most common device is DVL (Doppler Velocity Log) with accuracy up to ±0.1 cm/s [4]. This device can measure the velocity of AUV either relative to the sea bottom or water depending on...
altitude and equipment settings. Its main disadvantages are high cost and the inability of water-relative measuring in the coastal sea. Also, its variation called an Acoustic Doppler Current Profiler (ADCP) also is used for current profiling and vehicle velocity measuring [5]. An EM-log (an Electromagnetic log) is sometimes used for water-relative velocity measuring. However, it provides only relative to water AUV velocity estimation. EM-log is a sensor that provides velocity information, but unlike that of DVL, the output is relative velocity to water rather than absolute velocity, since the principle of EM-log is based on Faraday’s law which states electromagnetic induction [6]. Another device for AUV velocity measuring relative to water is a correlation velocity log (CVL). It is an ultrasonic navigation aid for marine applications, in which velocity is estimated using an acoustic transmitter and a receiver array. CVLs offer advantages over Doppler velocity logs in many autonomous underwater vehicle applications since they can achieve high accuracy at low velocities even during hover maneuvers [7]. The exotic and bio-inspired way of incoming flow sensing is the artificial lateral line with pressure sensors [8].

2. Quasi-steady thruster model

Quasi-steady modeling of thrust \( T \) and torque \( Q \) generated by an underwater thruster can be written in the terms of lift and drag curves with nondimensional thrust and torque coefficients \( K_T \) and \( K_Q \) [9, 10]:

\[
K_T(J_0) = \frac{T}{\rho D^4 n |n|}, \quad K_Q(J_0) = \frac{Q}{\rho D^4 n |n|}
\]  

(1)

where \( D \) is the propeller diameter, \( \rho \) is the water density, \( n \) is the propeller speed, and

\[
J_0 = \frac{v_a}{nD}
\]

(2)

is the advice ratio, where \( v_a \) is ambient water velocity.

The relationship between ambient water velocity and vehicle speed \( v \) in the steady state flow without ocean current is [11]

\[
v_a = (1 - w)v
\]

(3)

where \( w \) (typically 0.1–0.4 for ship) is denoted as the wake fraction number. We propose what for AUV the \( w \) parameter is negligible. So in our case \( v_a = v \) without ocean current.

The nondimensional thrust and torque coefficients can also be described by the following parameters [12]:

\[
K_T(J_0) = f_1(J_0, P/D, A^e/A_0, Z)
\]

\[
K_Q(J_0) = f_1(J_0, P/D, A^e/A_0, Z, R_n, t/c)
\]

(4)

where \( P/D \) is the pitch ratio, \( A^e/A_0 \) is the expanded-area ratio, \( Z \) is the number of blades, \( R_n \) is the Reynolds number, \( t \) the maximum thickness of the blade section, and \( c \) the chord length of the blade section.

The thrust and propeller torque coefficients \( K_T(J_0) \) and \( K_Q(J_0) \) within limited limits can be linearly approximated as follows [13]:

\[
K_T(J_0) = K_T(0) - \alpha J_0
\]

\[
K_Q(J_0) = K_Q(0) - \beta J_0
\]

(5)

where \( K_T(0) \) and \( K_Q(0) \) is coefficients without ambient flow \( (v = 0) \) obtained by a bollard pull test, \( \alpha \) and \( \beta \) are nondimensional constants.

From Equation 2 and Equation 5 incoming flow velocity can be obtained as follows:

\[
v = \frac{1}{\beta} \left( K_Q(0)nD - \frac{Q}{\rho D^4 n |n|} \right)
\]

(6)
where $Q$ is the motor load torque that can be obtained from the steady-state motor model [14]:

$$Q = K_m I$$

(7)

where $I$ is motor current and $K_m$ is the motor torque coefficient.

Sometimes thrusters are tilted with respect to the longitudinal axis of the AUV. It must be counted during axial velocity estimation as follows:

$$v^i = \frac{v^i_1}{\cos \psi^i \cdot \cos \theta^i}$$

(8)

where $v^i$ AUV axial flow velocity estimated by the $i$-th thruster, $v^i_1$ is velocity determined by Equation 6 by the $i$-th thruster, and $\psi^i$ and $\theta^i$ are thruster tilt relative to the longitudinal axis in the horizontal and vertical plane, respectively.

3. Experimental results

3.1. AUV Description

AUV “MMT-3000” (Figure 1) was used for experimental validation of the presented method of propulsion-based estimation of the incoming flow. The vehicle propulsion system consists of three stern thrusters. Two thrusters are located in the horizontal plane. They are tilted with respect to the longitudinal axis and the horizontal plane by an angle of 22.5 and 8 degrees ($\delta$ and $\beta$ angle in the Figure 2, respectively). One thruster is located in the vertical plane and tilted to the longitudinal axis by an angle of 11.25 degrees ($\alpha$ angle in the Figure 2).

![Figure 1](image1.png) **Figure 1.** The overall view of the AUV "MMT-3000".

![Figure 2](image2.png) **Figure 2.** The principal structure of the propulsion system.

3.2. Thruster parameters

Each of the three thrusters making up the propulsion system of the AUV consists of an identical motor and a propeller. The brushless-DC motor “2 DBM 70-1,1-1,3-3” and a specially made three-blade propeller were used for these thrusters. Parameters of the motor and propeller are listed in Table 1.

The initial polynomial describing the $K_T$ and $K_Q$ parameter of propeller was obtained by the regression database [15]. During the bollard pull test of the AUV thruster the $J_0(0)$ point of the polynomials was calculated. The refining $K_T$ and $K_Q$ depending on advice ratio (Equation 2) are presented in Figure 3 and listed in Table 2. Both coefficients were linearized within the advice ration region of $[0, 0.5]$. The Figure 4 and Figure 5 show results of the bollard pull test of the AUV thruster.
Table 1. Motor and propeller parameters of the AUV thruster.

| Parameter                | Value       | Parameter                | Value       |
|--------------------------|-------------|--------------------------|-------------|
| Armature Voltage, U      | 24 V        | Number of Blades, Z      | 3           |
| Phase Resistance, R      | 0.190 Ohm   | Diameter, D              | 0.19 m      |
| Rotor Inertia, J         | 2.5 \cdot 10^{-4} kgm^2 | Pitch Ratio, P/D         | 0.87        |
| Number of Poles, P       | 8           | Area Ratio, A/AD         | 0.4         |
| EM Time Constant, T\text{em} | 0.4 ms     |                          |             |
| Torque Coefficient, K_{m} | 0.070 Nm/A |                          |             |

Table 2. Polynomial approximation of $K_T$ and $K_Q$ propeller parameter.

$$
K_T = -0.096J_0^2 - 0.277J_0 + 0.3519
$$

$$
K_Q = -0.014J_0^2 - 0.0301J_0 + 0.0456
$$

$$
K_{T\text{lin}} = -0.3256J_0 + 0.3558
$$

$$
K_{Q\text{lin}} = -0.0373J_0 + 0.0462
$$

Figure 3. Refining $K_T$ and $K_Q$ thruster coefficients based on bollard pull test results.

Figure 4. Steady-state motor torque depending on square shaft rotation.

Figure 5. Steady-state thrust depending on square shaft rotation.

3.3. Experiment setup

The experimental validation of the method for propulsion-based estimation of the incoming flow was conducted by post-analysis of the dataset obtained during vehicle hydrodynamic coefficients estimation. This procedure is the vehicle's forward motion with a set of different velocities and constant value of target depth and yaw.

The vehicle motion trajectory for vehicle hydrodynamic coefficients estimation consists of round trip tack between the point of start located on the shore and finish located in the sea. This trajectory ensures the elimination of the tidal current effect on hydrodynamic coefficients evaluation. First tack (from the
start point to the point of the tack’s end) we used for calibration of the $\beta$ parameter in Equation 5 (Figure 6) because it cannot be measured during the bollard bull test and the second tack (from the endpoint to the point of start) we used for method validation. Propeller rotation and motor current of each AUV thruster during the entire vehicle motion trajectory are presented in Figure 8 and Figure 9, respectively.

Figure 6 shows there is no ocean or tidal currents due to equal velocity value on both tacks. Figure 7 presents the thrusters’ advice ratio within the entire vehicle trajectory.

3.4. Results

During the calibration step (see Figure 6), the parameter $\beta$ was obtained with the least-squares method:

$$
\min \left\{ \sum_{i=1}^{N} (v_d - v_i(\beta))^2 \right\}
$$

where $v_d$ is forward velocity obtained from the DVL and $v_i$ ($i = 1, ..., N$ where $N$ is the number of thrusters) is velocity obtained from thrusters by Equation 6. Figure 10 shows propulsion-based estimation of the incoming flow for each thruster with the fitted parameter $\beta = 0.0372$. Velocity obtained from DVL is presented in the figure. The average propulsion-based velocity $v^a$ (Equation 10) of incoming flow on the validation step is presented in Figure 11.

$$
v^a = \frac{1}{N} \sum_{i=1}^{N} v_i
$$

where $v_i$ ($i = 1, ..., N$ where $N$ is the number of thrusters) is velocity obtained from thrusters by Equation 6.
Figure 10. Propulsion-based velocities estimation on the calibration step with the fitted parameter $\beta = 0.0372$.

Figure 11. Propulsion-based average velocity estimation on the validation step with the fitted parameter $\beta$.

4. Conclusion and future work
The propulsion-based method for estimation of incoming flow is presented in the paper. The quasi-steady model of the thruster is used for velocity estimation. The linearized parameters of the thruster model are obtained by the bollard pull experiment and sea trial. The incoming flow estimation is compared with DVL data in case of tidal current absence. Velocity estimation error between methods is less than 0.1 m/s in a steady motion and less than 0.2 m/s in the transition process.

Future work will be devoted to the estimation of the AUV angle of attack and sideslip based on propulsion-based velocity evaluation.

5. References
[1] Dang F and Zhang F 2018 Distributed flow estimation for autonomous underwater robots using POD-based model reduction In 2018 IEEE Conference on Decision and Control (CDC) pp 4453-4458
[2] Page B R, Ziaee S, Pinar A J and Mahmoudian N 2016 Highly maneuverable low-cost underwater glider: Design and development IEEE Robotics and Automation Letters 2(1) pp 344-349.
[3] Palmer A, Hearn G E and Stevenson P 2008 Modelling tunnel thrusters for autonomous underwater vehicles IFAC Proceedings Vol 41(1) pp 91-96
[4] Hegrenæs Ø, Ramstad A, Pedersen T and Velasco D 2016 Validation of a new generation DVL for underwater vehicle navigation In 2016 IEEE/OES Autonomous Underwater Vehicles (AUV) pp 342-348
[5] Stanway M J 2010 Water profile navigation with an acoustic Doppler current profiler In OCEANS'10 IEEE Sydney pp 1-5
[6] Cha J, Ju H, Park C G, Yoo K and Park C 2019 Integration of Inertial Navigation System with EM-log Using H-infinity Filter In E3S Web of Conferences 94 p 01013
[7] Boltryk P, Hill M, Keary A, Phillips B, Robinson H and White P 2004 An ultrasonic transducer array for velocity measurement in underwater vehicles Ultrasonics 42(1-9) pp 473-478
[8] Salumäe T and Kruusmaa M 2013 Flow-relative control of an underwater robot Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 469(2153) pp 20120671
[9] Fossen T I 1999 Guidance and control of ocean vehicles University of Trondheim, Norway, Printed by John Wiley & Sons (Chichester, England) ISBN: 0 471 94113 1
[10] Whitcomb L L and Yoerger D R 1999 Development, comparison, and preliminary experimental validation of nonlinear dynamic thruster models IEEE journal of oceanic engineering 24(4) pp 481-494
[11] Lewis E V 1988 Principles of Naval Architecture Jersey City NJ: Soc. Naval Architects and Marine Eng.
[12] Oosterveld M W C and van Oossanen P 1975 Further computer-analyzed data of the Wageningen B-screw series *International shipbuilding progress* **22**(251) pp 251-262

[13] Fossen T I and Blanke M 2000 Nonlinear output feedback control of underwater vehicle propellers using feedback form estimated axial flow velocity *IEEE Journal of oceanic Engineering* **25**(2) pp 241-255

[14] Zhao L, Zhang X and Ji J 2015 A torque control strategy of brushless direct current motor with current observer *In 2015 IEEE International Conference on Mechatronics and Automation (ICMA)* pp 303-307

[15] Oosterveld M W C and van Oossanen P 1975 Further computer-analyzed data of the Wageningen B-screw series *International shipbuilding progress* **22**(251) pp 251-262