TEST PLATFORM PARADIGM FOR UNDERWATER DYNAMICS MEASUREMENTS

Xinyu Zeng, PhD Student; Svyatoslav Yatsyshyn, Dr.Sc., Prof.;
Lviv Polytechnic National University, Ukraine, E-mail: foreverlemon99@gmail.com

https://doi.org/10.23939/istcmtm2024.01.029

Abstract. This paper presents a test platform paradigm for underwater dynamics measurement. The platform aims to address the limitations of current measurement techniques and provide a comprehensive understanding of underwater dynamics. The proposed platform incorporates advanced control systems and compensation techniques to improve the accuracy and reliability of measurements. The effectiveness of the platform is demonstrated through experimental results, showing improved performance compared to existing methods. The test platform paradigm offers a promising approach for underwater dynamics measurement in various applications.

Key words: Test platform, Underwater dynamics measurement, Control system, Compensation technique.

1. Introduction

Accurate measurement of underwater dynamics is crucial for various applications such as underwater robotics, oceanographic research, and environmental monitoring. However, existing measurement techniques suffer from limitations such as unstable oscillations and nonuniform behavior. These limitations are often caused by thruster dynamics and nonlinearities in the system. To overcome these challenges, a new test platform paradigm is proposed. The proposed test platform paradigm integrates advanced control systems and compensation techniques to improve the accuracy and reliability of underwater dynamics measurement. By considering the nonlinear response of torque-controlled thrusters, the platform aims to reduce the effects of thruster dynamics and achieve stable and uniform behavior over the entire operating range. The platform also incorporates adaptive sliding controllers to compensate for uncertainties and degradation of thruster performance.

2. Drawbacks

Current measurement techniques for underwater dynamics often fail to provide accurate and reliable results due to the limitations mentioned earlier. These drawbacks can lead to inaccurate data interpretation and hinder the progress of underwater research and applications. Therefore, there is a need for a new test platform paradigm that addresses these drawbacks and provides more robust and precise measurements.

3. Goal

The goal of this work is to develop a test platform paradigm for underwater dynamics measurement that overcomes the limitations of current techniques. The platform aims to improve the accuracy, stability, and uniformity of measurements by incorporating advanced control systems and compensation techniques.

4. General Description of a Thruster

A propeller is a device used to generate thrust in underwater vehicles (Fig.1). It typically consists of a rotating screw-like blade that pushes water backward to create propulsion. The direction of thrust can be altered by reversing the rotation of the propeller. The performance of a propeller is crucial for the control and movement of underwater vehicles. The performance of a propeller can be described using various parameters, including thrust, propeller speed, and output flow velocity. The thrust of a propeller is directly proportional to the square of its propeller speed, while the output flow velocity depends on thrust, propeller speed, and propeller efficiency.

To accurately describe the dynamic characteristics of a propeller, researchers have constructed a physical system model based on force and torque feedback to reflect the propeller's thrust. This model uses the propeller angular velocity as the dynamic state variable and controls the propeller's motion through input torque. In this experiment, we selected propellers manufactured by ROV-MAKER and controlled the output current using Pulse Width Modulation (PWM) to regulate the propeller's output torque, thereby generating thrust underwater[1].

In PWM control, the pulse width range is 1000-2000 microseconds, with 1500 corresponding to the motor's midpoint. In other words, when PWM outputs 1500 microseconds, the motor remains stationary. As the control signal increases linearly from 1500 to 2000 microseconds, the motor rotates forward, and the speed linearly increases. Conversely, during the decreasing process from 1500 to 1000 microseconds, the motor reverses, increasing its speed[2].

Fig. 1. Using propellers manufactured by ROVMAKER, voltage supply range: 3s-6s, maximum passing current 15A, waterproof to a depth of 300 m underwater surface

5. Lumped Parameter Model Development

A standard thruster configuration, illustrated in Figure 1, comprises a stationary shroud and a propeller propelled by a torque-generating mechanism (T) operating at angular velocity (ω). The thruster's shroud possesses a cross-sectional area (A) and encloses a volume (V). The surrounding fluid has a density (ρ) and a volumetric flow rate passing through the thruster (Q)[3].

The model development is simplified by the following assumptions (Figure 2):

1. Negligible kinetic energy of the external fluid environment.

2. Negligible friction losses in the motor and propeller blades.

3. Incompressibility of the ambient fluid.

4. Maintaining parallel flow direction at the inlet and outlet of the thruster, disregarding rotational flow effects.

A state function of the volumetric flowrate Q can be used to express the kinetic coenergy T^* [4] of the fluid in the thruster:

$$T^*(QQ) = \frac{1}{2}\rho V \left(\frac{QQ}{A}\right)^2 \quad (1)$$

Defining a generalized momentum as:

$$\Gamma = \frac{dT^*}{dQQ} = \rho V \frac{QQ}{A^2} \quad (2)$$

The above relation is that of inertia (momentum related by a static constitutive law to the flow in bond-graph nomenclature with the effort variable Γ and flow variable QQ.

Γ has units of momentum/area and is referred to as the pressure momentum. Since the energy relations are linear, the conergy and energy have equal magnitudes, and the kinetic energy T can be expressed as a state function of the pressure momentum Γ:

$$(\Gamma) = \frac{A^2}{2\rho V}\Gamma^2 \quad (3)$$

The pressure momentum relation that follows from a power balance is as follows:

$$\frac{dT}{dt} = \frac{A^2}{\rho V}\Gamma\Gamma = \Omega\tau - KQQ \quad (4)$$

The power input from the thruster propeller is represented by $\Omega\tau$, the outgoing kinetic energy per volume is represented by K, and the time rate of change of the pressure momentum is shown by Γ.

It is possible to represent the departing kinetic energy per volume K as:

$$K = \frac{A^2\Gamma^2}{2\rho V^2} = \frac{\gamma\gamma^2}{2\rho} \quad (5)$$

where the $\gamma\gamma \equiv A\Gamma/V$ is the thruster's fluid momentum per volume.

The convected linear momentum, which is equal to the thrust created, connects the thruster and surrounding fluid:

$$\text{Thrust} = \gamma\gamma QQ \quad (6)$$

The thruster/propeller characteristics and angular velocity Ω can be linked to the volumetric flow rate, provided that the propeller does not cavitate. Slip is the term used to describe the discrepancy between a propeller's theoretical and actual advance per revolution. It is commonly stated as a ratio σ as follows:

$$\sigma = \frac{\Omega pA - QQ}{\Omega pA}, \quad (7)$$

where p, also known as the pitch, is the axial distance the propeller blades move for every unit of revolution (1 rad).

The equation above indicates that QQ (Ω) can be expressed as:

$$QQ = \eta pA\Omega, \quad (8)$$

where $\eta \equiv 1 - \sigma$ is referred to as the propeller efficiency. From equation (2)(4)(6)(8), the following thruster dynamic state and output equations are formed:

$$\Gamma = \frac{\tau}{\eta pA} - K \quad (9)$$

$$\text{Thrust} = \gamma\gamma QQ \quad (10)$$

The propeller angular velocity R can be used as the thruster dynamic state variable in the thruster dynamic state and output equations if we assume that the propeller efficiency (η), pitch (p), and duct area (A) are constants:

$$\Omega = \frac{\tau}{\eta^2p^2\rho V} - \frac{\eta pA}{2V}\Omega|\Omega| \quad (11)$$

$$\text{Thrust} = A\rho\eta^2p^2\Omega|\Omega| \quad (12)$$

Keep in mind that, as was previously stated, the steady-state thrust force is proportionate to the input torque.

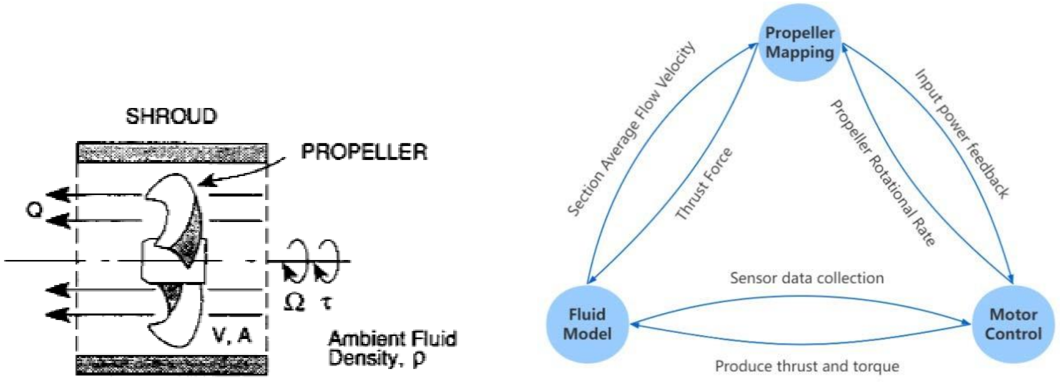

Fig. 2. Major Elements of the Model

6. Thruster validation (response rate, thruster thrust, torque produced, phase lag fit)

The model was validated using a thruster mounted in a rack in an aluminum-type table that instrumented the device to measure the output force and torque. As shown in Fig.3, the thrust was measured by a six-component force transducer using a D6045A sensor from DMI (Digitalize Miniaturize Inteligentized), Inc. in a matrix decoupling technique in order to decompose the output signal of the six-axis force transducer into its force and torque components in different directions and complete the recording. A series of static tests were carried out to confirm the previously proposed model and to determine specific parameter values a, 0, and Ct [5]. Based on the available measurement data, it was possible to confirm that these parameters were reasonable for the physical parameters of propeller efficiency and volume involved.

7. Thruster Test

The thruster served as the test object for a number of dynamic thrust measurement tests. Both a succession of current-commanded step input signals encompassing a broad range of input levels and a long-period sinusoidal waveform input signal were used in these tests [6].

Measured variables include motor input current, voltage, and current instructions as well as motor speed and net thrust. These measurements are all dynamic and are collected at a sample rate of 50 Hz.

7.1. Long Period Triangular Wave Inputs

We decided to output long-period sine wave signals for the measurement of thrust generation before and after to produce robust output results. The results are displayed in Figure an as a function of motor speed over 60 seconds for the thrust produced in the X-axis and the torque produced in the Y-axis. The inputs for current and voltage with varying speeds are shown in Fig. 4. The speed versus force generated for the steady state instance is shown in Fig.5. This number is consistent with the idea that predicted thrust is inversely proportional to propeller speed. Due to the strong link between and current inputs, the current/thrust behavior is best described by the square law relationship.

Fig. 3. Direct coupling relationship between thrusters and sensors

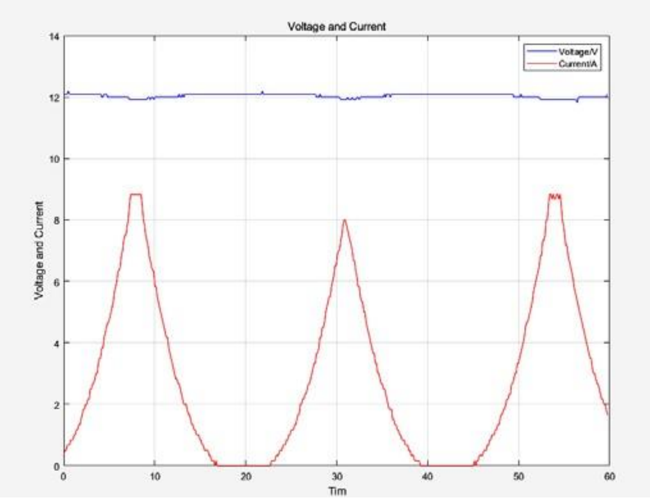

Fig. 4. The rotational speed changes in a sinusoidal waveform and outputs the corresponding current and voltage input signals.

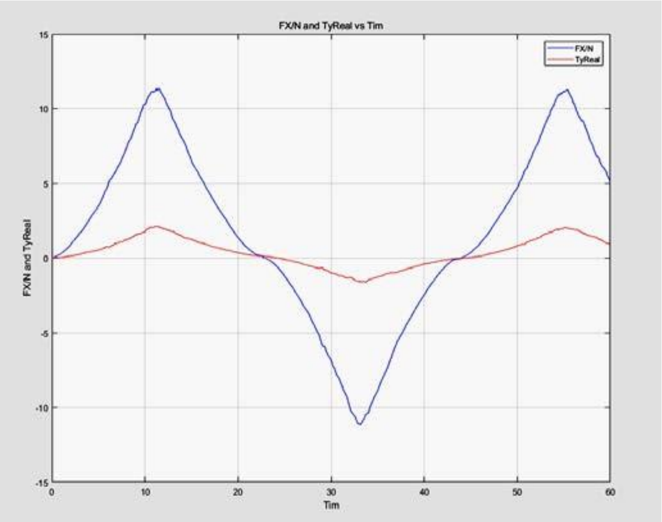

Fig. 5. The thrust generated by the thruster in the direction of the sensor's X-axis and the moment generated by the Y

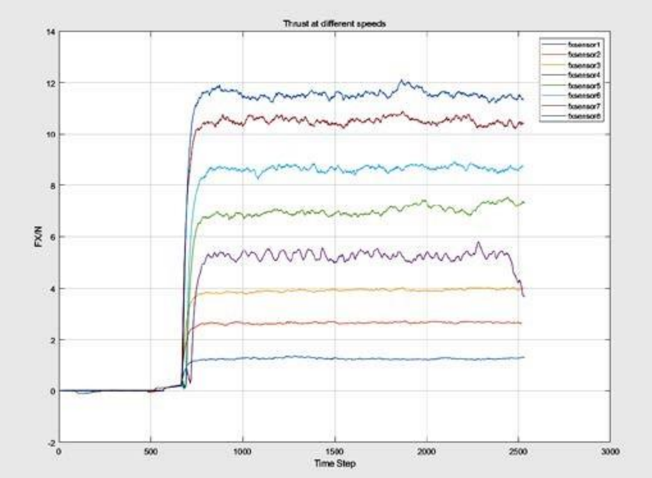

Fig. 6. Different rotational speeds corresponding to the force generated

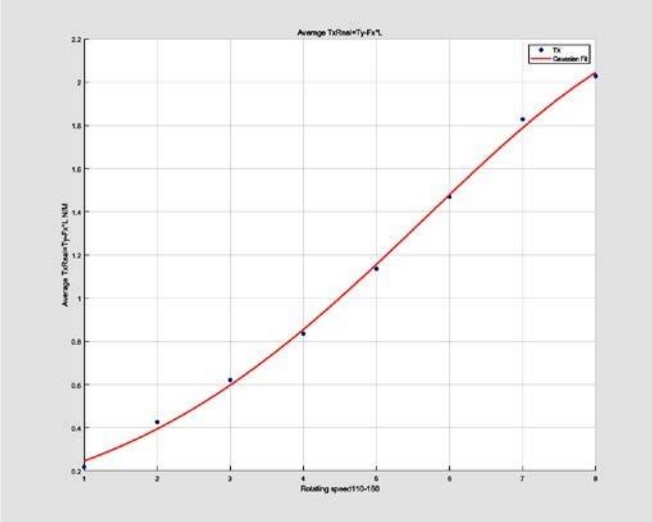

Fig. 7. Linear relationship with rotational speed exhibited
by the mean values of the 8 force groups under Gaussian regression

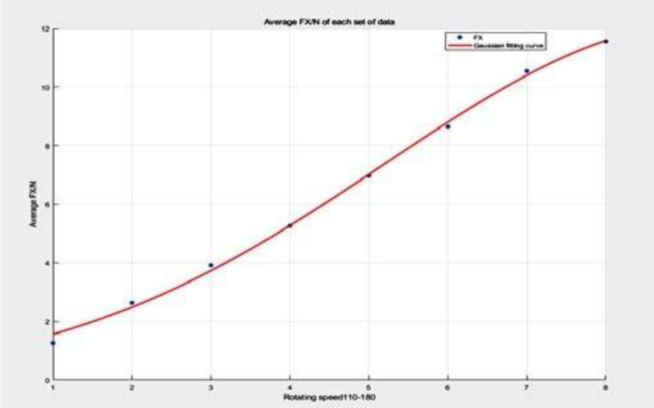

Fig. 8. A linear relationship with rotational speed exhibited by the mean values
of 8 sets of moments under Gaussian regression

7.2. Step Input Effects of Amplitude.

In this experiment, step signals of varying amplitudes were put up to regulate the motor's current and, consequently, its speed. The influence of rotational speed from 0 to the force corresponding to the steady state reached after the step control signal was recorded using eight different sets of current inputs with the same time step setting. It was established that the thruster's force output's steady-state value depends on its current value [7].

8. Conclusions

1. In the current work, there was developed a test platform paradigm for underwater dynamics measurement that overcomes the limitations of current techniques and is able to improve the accuracy, stability, and uniformity of measurements by incorporating advanced control systems and compensation techniques.

2. The considered platform adapts to uncertainties and degradation of thruster performance through the use of adaptive sliding controllers which is demonstrated through experimental validation, showcasing its superiority over existing methods.

3. The proposed test platform paradigm offers a promising approach for underwater dynamics measurement providing more accurate and reliable measurements in various applications for advancing underwater research and technology.

9. Gratitude

The authors express their gratitude to the Department of Information-Measuring Technologies of Lviv Polytechnic University, Ukraine, for the support.

10. Conflict of Interest

The authors state that there are no financial or other potential conflicts regarding this work.

References

[1] M. N. Bandyopadhyay, “Position Control System of A PMDC Motor”. Department of Electrical Engineering, Kolkata,West Bengal, India 2016,
DOI: 10.1109/ICEEOT.2016.7754785

[2] H. Øveraas, Dynamic Positioning Using Model Predictive Control With Short-Term Wave Prediction”, 2023, Department of Engineering Cybernetics, Norwegian Univer- sity of Science and Technology, Trondheim, Norway, DOI: 10.1109/JOE.2023.3288969

[3] D.R. Yoerger, “The Influence of Thruster Dynamics on Underwater Vehicle Behavior and Their Incorporation in- to Control System Design”, Deep Submergence Laborato- ry, Department of Applied Physics and Ocean Engineer- ing, Woods Hole Oceanographic Institution, Woods Hole, MA, USA,1990. DOI: 10.1109/48.107145

[4] M. Gertler and G. R. Hagen, “Standard equations of mo- tion for submarine simulations” Naval Ship R&D Center, Bethesda, MD, NSRDC Rep. No. 2510, 1967. [Online]. Available: https://apps.dtic.mil/sti/citations/AD0653861

[5] Z. Liang, “Dynamic Analysis and Path Planning of a Turtle-Inspired Amphibious Spherical Robot”, School of Electronic Information Science and Technolo- gy, China, 2022 [online]. Available: https://www.mdpi. com/2072-666X/13/12/2130#

[6] A. J. Healey, “Toward an Improved Understanding of Thruster Dynamics for Underwater Vehicles”, Naval Postgraduate School, Department of Mechanical Engi- neering, Monterey CA,1994. DOI: 10.1109/48.468242

[7] Y Sun, “Experimental and numerical analyses of the hydrodynamic performance of propeller boss cap fins in a propeller-rudder system”, Science and Technology on Underwater Vehicle Laboratory, Harbin Engineering Uni- versity, China, 2016. [Online]. Available: https://www.tandfonline.com/doi /full/10.1080/19942060.2015.1121838.

[8] M. Abkowitz, “Stability and Motion Control of Ocean Vehicles”, Cambridge, MA: MIT Press, 1969. [Online]. Available: https://pdfcoffee.com/abkowitz-stability-and- motion-control-of-ocean-vehicles-pdf-free.html

[9] Cody, S. E., “An Experimental Study of The Response of Small Thrusters to Step and Triangular Wave Inputs”, Monterey, CA,1992.[Online]. Available: https://www.sciencedirect.com/science/article/pii/S14746 67017371008

[10] Adams, J.C., Burton, D., Lee, M., “Dynamic Characteri- zation and Control of Thrusters for Underwater Vehicles”,1991.

[11] Brown, J. P., "Four Quadrant Model of the NPS AUV 11 Thruster" Monterey, CA, 1993. [Online]. Available: https://core.ac.uk/download/pdf/36719905.pdf

[12] D. Graham, D. McRuer, "Analysis of Nonlinear Control Systems", New York: Wiley, 1961. [Online]. Available: https://scholar.google.com.ua/scholar?q=D.+Graham,+D. +McRuer