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Adaptive Fuzzy Sliding Mode Controller and Observer for a Dive Cell

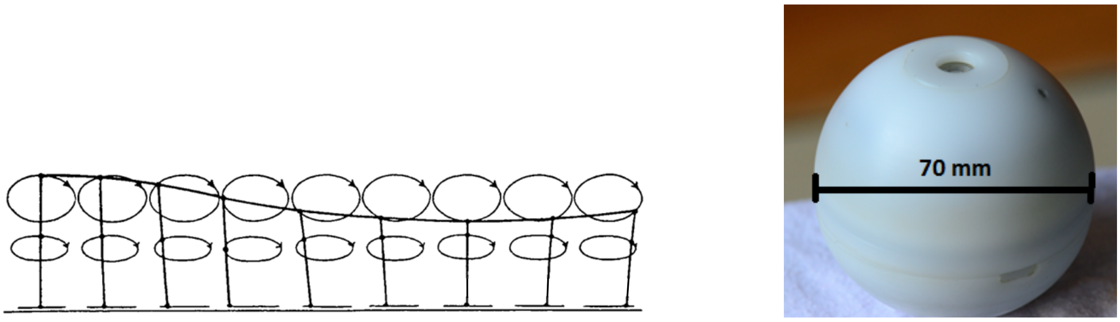
Wallace M. Bessa[2], **Edwin Kreuzer**[1], **Ludwig Krumm**[1], **Marc-André Pick**[1], and **Eugen Solowjow**[1,*]

[1] Institute of Mechanics and Ocean Engineering, Hamburg University of Technology (TUHH), 21073 Hamburg, Germany
[2] Departamento de Engenharia Mecânica, Universidade Federal do Rio Grande do Norte, 59072-970, Natal, RN, Brazil

We present an adaptive fuzzy sliding mode control strategy in combination with a sliding mode observer for a dive cell. Numerical results demonstrate the outperformance of the presented controller compared to a conventional sliding mode approach.

1 Introduction

Water particles move on orbitals under the influence of surface gravity waves as illustrated in Fig. 1(a). These orbitals are usually visualized by laborious optical methods. A dive cell was developed at the Institute of Mechanics and Ocean Engineering, TUHH for the analysis of water particle orbitals, see Fig. 1(b). The dive cell is supposed to reach and stay on an isobar, where the average density of the dive cell equals the density of the surrounding water. The dive cell then describes the same trajectories as the water particles. The design is composed of a pressure sensor, a micro controller and an actuator to alter the volume of the dive cell to control buoyancy. Furthermore, an acceleration sensor and a mounted SD card provide the possibility to analyze the kinematics of the dive cell, hence of the water particle trajectories. In order to reach and stay on a certain isobar an adaptive fuzzy sliding mode controller (AFSMC) strategy is developed following [1].



(a) Illustration of water particle orbitals under the influence of surface waves [2].

(b) Photograph of the dive cell developed at the Institute of Mechanics and Ocean Engineering, TUHH.

Fig. 1: Dive cell design for the analysis of water particle orbitals.

2 Model

The equation of motion of the dive cell is derived under the consideration of quadratic viscous damping and reads

$$\ddot{z} = \frac{1}{m}\left[\rho_w g(V_0 - V_w) - mg - k\dot{z}|\dot{z}|\right], \tag{1}$$

with z being the current depth position, the mass of the dive cell is m, the water density ρ_w, the gravitational acceleration g and the viscous damping coefficient k. The value V_w is the adjustable volume of the dive cell used for controlling the buoyancy, while V_0 represents the volume corresponding to zero buoyancy. For the above design $V_0/V_w \approx 40$. Due to the nonlinear damping and the uncertain parameters, such as the hydrodynamic added mass, a sliding mode control (SMC) approach is chosen for the design of the controller and observer, which has proven to be a well-established methodology for robust nonlinear controller synthesis in the presence of modeling imprecisions and external disturbances. The control goal is to stabilize the dive cell at an isobar which coincides with the dive depth z_{des} in absence of waves.

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[*] Corresponding author: eugen.solowjow@tuhh.de

3 Controller and Observer Design

We define a sliding surface $s = \dot{\tilde{z}} + \lambda \tilde{z}$, where $\tilde{z} = z - z_{\text{des}}$. The control law for the actuated volume of the dive cell consists of four parts:

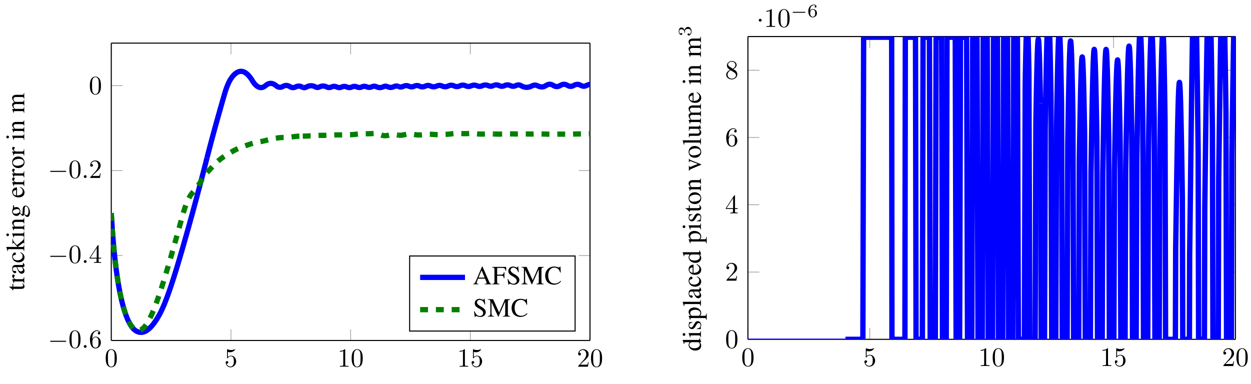
$$V_W = \frac{1}{\rho_w g}\left[\underbrace{V_0 \rho_w g - mg - k\dot{z}|\dot{z}|}_{①} + \underbrace{m\lambda\dot{\tilde{z}}}_{②} + \underbrace{\eta\,\mathrm{sat}(\frac{s}{\Phi})}_{③} + \underbrace{\hat{d}}_{④}\right]. \tag{2}$$

The first term ① is intended to cancel the known dynamics. Term ② imposes the desired dynamics on the system. In order to account for model errors and uncertainties, we include the robustness term ③. The robustness term is often chosen such that the sliding condition $\frac{1}{2}\frac{\mathrm{d}}{\mathrm{d}t}s^2 \leq -\eta\, s\,\mathrm{sgn}(s)$ is satisfied, where η is a strictly positive constant. However, the implementation of a discontinous controller can result in "chatter". Therefore, we replace the sign function by the saturation function in our design. The desired condition becomes $\frac{1}{2}\frac{\mathrm{d}}{\mathrm{d}t}s^2 \leq -\eta\, s\,\mathrm{sat}(\frac{s}{\Phi})$. With the sign function we can guarantee $s \to 0$ in finite time. The saturation function only guarantees s to reach and stay within a boundary layer of width Φ, which results in a steady state error. In order to compensate for the steady state error, the term ④ provides disturbance estimation [1]. It is computed by the adaptive fuzzy inference system $\hat{d}(s) = \hat{\mathbf{D}}^{\mathrm{T}}\,\boldsymbol{\Psi}(s)$, with $\boldsymbol{\Psi}(s) = [\psi_1(s),\ \psi_2(s), \cdots,\ \psi_N(s)]$ being a normalized vector which contains N fuzzy membership functions ψ_i. Vector $\hat{\mathbf{D}}$ is updated by $\dot{\hat{\mathbf{D}}} = -\varphi\, s\,\boldsymbol{\Psi}(s)$, where φ is a positive constant.

Since we can only take pressure measurements, a sliding mode observer [3] is included for the estimation of the velocity $\dot{z}$. We introduce an injection term $\dot{\hat{z}} = \nu$ which is the velocity estimate of interest and choose $\nu = -\kappa\,\mathrm{sgn}(\hat{z} - z)$. Solving $\tau\dot{\nu} = -\nu - \kappa\,\mathrm{sgn}(\hat{z} - z)$ for ν provides the velocity estimate required for the control law (2).

4 Numerical Results and Discussion

We demonstrate the performance of the AFSMC in comparison to the SMC by means of a numerical simulation. The dive cell is released with an initial tracking error of $-0.3\,\mathrm{m}$ and an initial velocity of $-1\,\frac{\mathrm{m}}{\mathrm{s}}$. The assumed mass of the dive cell has an error of $20\,\%$. Furthermore, a permanent stochastic forcing acts on the dive cell. Figure 2(a) demonstrates the tracking error for both controllers. As expected, the SMC is not able to compensate for the steady state error because of the saturation function. The AFSMC provides the desired tracking. The actuator action for the AFSMC is shown in Fig. 2(b). Note, that the adjustable volume V_w is constrained by $0 < V_w < 9 \cdot 10^{-6}\,\mathrm{m}^3$.



(a) Tracking error for the SMC and AFSMC.

(b) Actuator action for the AFSMC.

Fig. 2: Numerical results for dive cell starting with a negative initial velocity.

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