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Identification of the equivalent linear dynamics and controller design for an unmanned underwater vehicle

Afshin Banazadeh[a,*], Mohammad Saeed Seif[b], Mohammad Javad Khodaei[b], Milad Rezaie[b]

[a] Sharif University of Technology, Department of Aerospace Engineering, PO Box: 11365-11155, Tehran, Iran
[b] Sharif University of Technology, Department of Mechanical Engineering, Tehran, Iran

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ABSTRACT

This paper investigates the applicability of frequency-domain system identification technique to achieve the equivalent linear dynamics of an autonomous underwater vehicle for control design purposes. Frequency response analysis is performed on the nonlinear and coupled dynamics of the vehicle, utilizing the CIFER® software to extract a reduced-order model in the form of equivalent transfer functions. Advanced features such as chirp-z transform, composite window optimization, and conditioning are employed to achieve high quality and accurate frequency responses. A particular frequency-sweep input is implemented to the nonlinear simulation model to achieve pole-zero transfer functions for yaw and pitch motions that were previously developed by the perturbed equations of motion. To evaluate the accuracy of the identified models, zig-zag test data are compared with the predicted responses for both identified and linearized models in time domain. The results show that the identified models perform significantly well in the presence of noise and model uncertainties with the maximum error of 12%, thanks to the precise spectral analysis. Proportional-integral controllers are designed based on the extracted models and tracking performance is experimentally demonstrated by several test results that show the ability of the vehicle to navigate autonomously and follow the GPS waypoints with reasonable accuracy.

1. Introduction

Marine industry utilizes new technologies to meet the growing needs for exploration or extraction of undersea resources, inspection, environmental data collection, and installation or maintenance of coastal structures. Due to some restrictions of deep-sea explorations, autonomous underwater vehicles are the most powerful means for subsurface studies that help researchers with simple, low-cost, and rapid response capabilities through appropriate underwater data collections. However, the dynamics of these vehicles are complex with several nonlinear and coupled terms, which make it a challenging task to perform identification process for dynamic stability analysis and control design. Several approaches are proposed to model underwater vehicles that contain hydrodynamic coefficients (Fossen, 1994; Yuh, 1990). Commonly-used methods for modeling of underwater vehicles can be classified in four major categories (Xu et al., 2013). These categories include captive model test with planar motion mechanism (PMM) (Rhee et al., 2000), estimation with empirical formulas (Silva et al., 2007), numerical calculation based on computational fluid dynamics (CFD) (Toxopeus, 2009), and system identification (SI) in combination with free-running model. Identification of marine vehicles is a highly versatile procedure for rapidly and efficiently extracting accurate dynamic models of a marine vehicle from the measured response to specific control inputs (Tischler and Remple, 2006). Various identification techniques have been developed since the 1950s for system dynamic modeling, parameters and states estimation, using nonlinear simulation and measurement data. Neural network (NN) (Mahfouz and Haddara, 2003; Shafiei and Binazadeh, 2015), support vector machines (SVM) (Zhang and Zou, 2011; Xu et al., 2013), time domain identification (Naeem et al., 2003; Shi and Zhao, 2009, Avila et al., 2013) and frequency domain identification (Selvam et al., 2005; Bhattacharyya and Haddara, 2006; Perez and Fossen, 2011) are the most applicable identification techniques used for marine vehicles. However, most of the published studies have focused on parameter estimation and presenting some approaches to measure hydrodynamics coefficients of ships and AUVs. For the control purpose, it is desirable to simplify and reduce the nonlinear and coupled dynamics of marine vehicles to equivalent linear models (Tiano et al., 2007). However, little attention has been paid to the frequency domain characteristics despite its advantages and restrictions of time domain.

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* Corresponding author.
E-mail addresses: banazadeh@sharif.edu (A. Banazadeh), seif@sharif.edu (M.S. Seif), khodaei_mjavad@alum.sharif.edu (M.J. Khodaei), Rezaie_milad@mech.sharif.edu (M. Rezaie).

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Nomenclature

XYZ	Earth-fixed frame
xyz	Body-fixed frame
X, Y, Z	External forces in the body-fixed frame
K, M, N	Moments of external forces in the body-fixed frame
u, v, w	Linear velocities in body-fixed frame
p, q, r	Rotational angular velocities
ϕ, θ, ψ	Euler angles
I_x, I_y, I_z	Mass moments of inertia in the body-fixed frame
x_G, y_G, z_G	Center of gravity in the body-fixed frame
x_B, y_B, z_B	Center of buoyancy in the body-fixed frame
CB	Center of buoyancy
CG	Center of gravity
M_t	Inertia matrix
M_A	Added inertia matrix
M_{RB}	Rigid-body inertia matrix
$C_{RB}(V)$	Rigid-body Coriolis and centripetal inertia matrix
$C_A(V)$	Hydrodynamic Coriolis and centripetal matrix
$D(v)$	Hydrodynamic damping matrix
$g(\eta)$	Restoring forces and moments matrix
τ	Propulsion forces and moments matrix
δ_r	Rudder deflection
δ_s	Elevator deflection
K_T	Thrust force coefficient
K_Q	Thrust torque coefficient
n	Propeller revolution
J_0	Advanced number
W	Weight
B	Buoyancy
g	Gravitational Acceleration
m	Mass
ρ	Density
D	Propeller diameter
$X_{\dot{u}}$	Drag contribution in the longitudinal X direction due to time rate of change of u
X_{qq}	Drag force due to square of pitch rate of body
X_{rr}	Drag force due to square of yaw rate of body
X_{wq}	Drag force due to q and w
X_{vr}	Drag force due to r and v
$X_{u\|u\|}$	Drag force due to square of surge rate of body
X_{HS}	Restoring force in the longitudinal X direction
X_{Thrust}	Propulsion force in the longitudinal X direction
Y_{HS}	Restoring force in the longitudinal Y direction
$Y_{v\|v\|}$	Sway force due to square of sway of body
$Y_{r\|r\|}$	Sway force due to square of yaw rate of body
$Y_{\dot{v}}$	Sway force due to time rate of change of v
$Y_{\dot{r}}$	Sway force due to time rate of change of r
Y_{ur}	Sway force due to r and u
Y_{wp}	Sway force due to p and w
Y_{pq}	Sway force due to q and p
Y_{uv}	Sway force due to v and u
$Y_{\delta r}$	Sway force due to rudder deflection
Z_{HS}	Restoring force in the longitudinal Y direction
$Z_{w\|w\|}$	Heave force due square of w
$Z_{q\|q\|}$	Heave force due square of q
$Z_{\dot{w}}$	Heave force due to time rate of change of w
$Z_{\dot{q}}$	Heave force due to time rate of change of q
Z_{uq}	Heave force due to u and q
Z_{vp}	Heave force due to p and v
Z_{rp}	Heave force due to p and r
Z_{uw}	Heave force due to w and u
$Z_{\delta s}$	Heave force due to elevator deflection
K_{HS}	Restoring moment around X direction
$K_{\dot{p}}$	Roll moment due to time rate of change of p
K_{Thrust}	Propulsion moment around X direction
M_{HS}	Restoring moment around Y direction
$M_{w\|w\|}$	Pitch moment due to square of w
$M_{q\|q\|}$	Pitch moment due to square of q
$M_{\dot{w}}$	Pitch moment due to time rate of change of w
M_{uq}	Pitch moment due to q and u
M_{vp}	Pitch moment due to p and v
M_{rp}	Pitch moment due to p and r
M_{uw}	Pitch moment due to w and u
$M_{\delta s}$	Pitch moment due elevator deflection
N_{HS}	Restoring moment around Z direction
$N_{v\|v\|}$	Yaw moment due to square of v
$N_{r\|r\|}$	Yaw moment due to square of r
$N_{\dot{v}}$	Yaw Moment due to time rate of change of v
$N_{\dot{r}}$	Yaw Moment due to time rate of change of r
N_{ur}	Yaw moment due to r and u
N_{wp}	Yaw Moment due to p and w
N_{pq}	Yaw Moment due to p and q
N_{uv}	Yaw Moment due to v and u
$N_{\delta r}$	Yaw Moment due to rudder deflection
K_I	Integral controller gain
K_P	Proportion controller gain
$R(s)$	Desired input
$E(s)$	Error signal
$G_c(s)$	Transfer function of controller
$G_Y(s)$	Transfer function of actuator
$G_P(s)$	Transfer function of the system
$Y(s)$	Output vector
$u(t)$	Control signal

Using an equivalent linear model to study system dynamics is very popular due to the ease of analysis and maturity of controller design for the linear models. This technique has been used for more than 30 years for complicated systems like aircraft and marine vessels (Marchand and Fu, 1985; Källström and Åström, 1981; Selvam et al., 2005). It is much more convenient to provide a linear model of an underwater vehicle in the frequency domain rather than time domain due to unique features such as elimination of possible bias, sensor and process disturbances as well as less computational cost.

Banazadeh and Ghorbani (2013), derived a linear dynamic for a surface ship in frequency domain by representing transfer functions to design proper PID controllers using CIFER® (Comprehensive Identification from FrEquency Responses) software. Nikusokhan and Banazadeh (2014), introduced the frequency domain identification of a servo mechanism in the presence of backlash and friction, using the same software. In the current study, this software is utilized in the identification process, particularly to adapt and evaluate frequency responses. It is notable that, identification methods are partially dependent on the maneuvers performed and subsequent data sets. Therefore, development of a nonlinear simulation model would help to understand the dynamics and generating the required data for the identification purpose. Finally, the best linear approximation of a nonlinear and coupled system is derived that will be used for non-parametric or parametric modeling to capture the key dynamic features of the system.

The aim of this paper is to evaluate the applicability of frequency domain identification to be used for a subsurface vehicle and to achieve the best reduced order equivalent linear model with the purpose of designing a proper controller. Designing an optimal excitation signal, data conditioning and proposing dynamic model of actuators are also considered.

In this paper, by using the well-known Fossen's model (Fossen, 1994), a nonlinear simulation model of an underwater vehicle is

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