Ocean Engineering 104 (2015) 359–369

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

H_∞ controller design using LMIs for high-speed underwater vehicles in presence of uncertainties and disturbances

Xiaoyu Zhang [a,*], Yuntao Han [a,*], Tao Bai [a], Yanhui Wei [a], Kemao Ma [b]

[a] *College of Automation, Harbin Engineering University, 150001 Harbin, China*
[b] *Control and Simulation Center, Harbin Institute of Technology, 150080 Harbin, China*

ARTICLE INFO

Article history:
Received 3 September 2014
Accepted 19 May 2015
Available online 11 June 2015

Keywords:
Underwater vehicles
Stability
H_∞ control
linear matrix inequalities (LMIs)

ABSTRACT

Traditional underwater vehicles are limited in speed due to dramatic friction drag on the hull. Supercavitating vehicles exploit supercavitation to reduce drag and increase their underwater speed. Compared with fully wetted vehicles, the nonlinearities in the models of cavitator, fin, and particularly nonlinear planing force make the control design of supercavitating vehicles more challenging. For a widely cited benchmark model, this paper reformulates the supercavitating vehicle model in a cascade form of subsystems to facilitate the application of the backstepping control design. Based on linear matrix inequalities (LMIs), we developed a new robust H_∞ controller by introducing the sector conditions of the nonlinear characteristics of nonlinear planing force. Simulations are conducted for both initial and tracking responses to evaluate the performance and robustness of the proposed H_∞ controller for all admissible uncertainties and disturbance inputs.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

For a high-speed moving object, there usually exist cavitation bubbles around the corner of sharp contours due to the flow separation caused by pressure gradients. This phenomenon is often observed when a propeller spins fast such that the surrounding liquid is vaporized due to the decrease in pressure, as is shown in Fig. 1. Cavitation is undesirable in most engineering applications (Kirschner et al., 2006, Fredette et al., 2006, Zou et al., 2013). Howerver, recent developments in supercavitation, motivated by the demand for high-speed underwater vehicles has stimulated renewed interest in cavitation. Flows exhibiting cavities which entirely envelop the moving body are categorized as supercavitating flows, in which the liquid phase does not contact the moving body over most of its length, which makes the skin friction drag almost negligible. Supercavitation can provide significant benefit for drag reduction by maintaining a stable single vaporized water bubble around the vehicle, which can potentially be used to extend the velocity range of underwater applications. Different from other conventional submarine bodies, supercavitating vehicles (SVs) lose most of the buoyancy because of the whole package within the cavity. Furthermore, the existence of strong nonlinear planing force and the change of cavity shape will bring great difficulties to the stability control and maneuver of SVs. Existing or notional SVs include projectiles, torpedoes, and underwater transport vehicles. Extensive research on SVs is being conducted in the US supported by the Navy and DARPA, as well as in Germany, Russia, Iran and China (Sturgeon, 2001, Serebryakov, 2002, Wu and Chahine, 2007, Zhang et al., 2007).

Dynamic models for SVs have been studied in a series of papers. The dynamics of uncontrolled supercavitating projectiles were studied in Kulkarni and Pratap (2000). The dynamic behavior of SVs were analyzed in Ruzzene and Soranna (2002). The vehicles are generally modeled as slender elastic beams in order to predict their dynamic response under "tail-slap" conditions in terms of rigid body motion as well as dynamic strains and vibrations. For the dive-plane dynamics, bifurcations with respect to a quasi-static variation of the cavitation number were studied in Lin et al. (2006a, 2007). The tailslap phenomenon of the supercavitating vehicle is identified as the consequence of a Hopf bifurcation followed by a grazing event. It is shown that the occurrence of these bifurcations can be delayed or triggered earlier by using dynamic linear feedback control aided by washout filters. A linear mathematical model of a supercavitating vehicle was developed to investigate some of the physical factors affecting stability and control in Mokhtarzadeh et al. (2012). Three cavitator shapes can result in unstable vehicles when operating in nonplaning conditions, with the disk cavitator the least destabilizing. A hybrid validation technique was presented to test mathematical models

* Corresponding authors.
E-mail addresses: zhangxiaoyu@hrbeu.edu.cn (X. Zhang), yuntaohan@163.com (Y. Han).

http://dx.doi.org/10.1016/j.oceaneng.2015.05.026
0029-8018/© 2015 Elsevier Ltd. All rights reserved.

Nomenclature

σ	cavitation number
ρ	fluid density (kg/m^3)
ρ_b	the supercavitating vehicle density (kg/m^3)
r_ρ	ratio of ρ_b to ρ, dimensionless
m	mass of the supercavitating vehicle (kg)
I_{yy}	moment of inertia about the body-fixed reference frame ($kg\ m^2$)
C_{x0}	cavitator drag coefficient at zero angle of attack
L	the supercavitating vehicle length (m)
L_g	location of the center of gravity in the body-fixed reference frame (m)
V	forward velocity (m/s)
θ	pitch angle (rad)
q	pitch rate (rad/s)
z	vertical position (m)
w	vertical velocity (m/s)
δ_c	cavitator angle with respect to the x-axis (rad)
δ_f	fin angle of attack in the body coordinates (rad)
α_c	cavitator angle of attack (rad)
α_f	fin angle of attack (rad)
α_p	angle of attack at the planing location (rad)
F_{cav}	cavitator hydrodynamic force (N)
F_{fin}	fin hydrodynamic force (N)
F_g	gravity force (N)
F_p	planing force (N)
M_g	gravity moment with respect to the center of pressure of the cavitator (N m)
M_{fin}	fin moment with respect to the center of pressure of the cavitator (N m)
M_p	planing moment with respect to the center of pressure of the cavitator (N m)
n	effectiveness of fins relative to the cavitator, dimensionless
R	radius of cylindrical section (m)
R_n	radius of the cavitator (m)
R_c	cavity radius at planing location (m)
R'	normalized difference between cavity and body diameter, dimensionless
h'	normalized immersion, dimensionless

and control systems for a supercavitating vehicle in Sanabria et al. (2013). The test method combines simulation of the vehicle motion, real-time experimental measurements of hydrodynamic forces acting on the vehicle wetted areas, and vehicle flight computer to evaluate the supercavitating vehicle performance subject to steady and unsteady flows. Unlike a fully-wetted vehicle for which the lift is generated by vortex shedding off the hull, a supercavitating vehicle is enveloped by gaseous surface and thus the lift is solely provided by control surface deflections of the cavitator and fins, as well as possible planing force due to tail-slap contact of the vehicle afterbody with the cavity. The nonlinearity in system dynamics, e.g., the nonlinear planing force as well as nonaffine dependence of the cavitator and fins on control surface deflections, makes the control design very challenging. In Kirschner et al. (2002), high-fidelity models of the cavitator and fins were used and a linear quadratic regulator (LQR) was designed for a straight and level flight and a bank-to-turn maneuvering. In the control and maneuvering of SVs, there exist present unique challenges associated with the distinctive operating conditions of SVs, which are affected by the location with respect to the center of gravity of the hydrodynamic force generated by the cavitator, the complex and nonlinear nature of the interactional forces between the vehicle and the cavity, and the dynamic nature of the cavity itself. A switching controller, which switches between two LQR controllers, designed for linear models with and without planing force, was presented in Shao et al. (2003). As a follow up, the same authors presented in Vanek et al. (2006a, 2006b and 2007) another switching control law which switches between feedback linearization controllers designed for models with and without planing force. In Lin et al. (2006b), controllers that provide absolute stability were designed by modeling the planing force as sector-bounded uncertainty, and a backstepping controller

Fig. 1. Water tunnel experiment on supercavitation.

was designed for the nominal system. A benchmark control problem was proposed by Dzielski and Kurdila (2003) for a supercavitating vehicle, and it was shown that instability can result from the bounce of the vehicle in the cavity due to its weight, which was referred to as the periodic impulse effect of the planing force. The development of effective control laws for SVs has received increasing attention in recent years (Goel, 2002 and Vanek, 2008, Vanek et al., 2010), which indirectly confirms the significant challenges posed by the problem. The sliding mode control and the quasi-linear parameter varying control were proposed for the dive plane dynamics model of the supercavitating vehicle, and a saturation compensator was designed to compensate for the physical limits on deflection angles of control surfaces of the cavitator and fins in Mao and Wang (2009). The pitch plane dynamics of the supercavitating vehicle modeled as a time-delay quasi-linear parameter varying system was reformulated and delay-dependent H_∞ controllers were developed in Mao and Wang (2011). In order to maintain the stability of the supercavitating vehicle in the turning process, a μ-synthesis controller based on bank-to-turn (BTT) scheme was designed for a pitch channel and a yaw-roll channel respectively in Zhao et al. (2014).

Uncertainties exist in supercavitating vehicles as a result of parameter variations and imprecise mathematical modeling. To analyze the robust stability and robust performance for the uncertain system, such as supercavitating vehicles, it generally needs to solve the relative H_∞ synthesis problem (Apkarian et al., 2011; Wang and Boyd, 2011). Currently, H_∞ synthesis problem is solved by dealing with Riccati equations. By this way, the H_∞ synthesis problem is transformed into the solvability of Riccati matrix equations, but there is no guarantee of convergence when solving Riccati matrix equations with iteration method, and there also may be some conservativeness caused by some parameters to be determined artificially. To avoid these disadvantages, an alternative method based on linear matrix inequalities (LMIs) was suggested to solve H_∞ synthesis problem, which can achieve a set of desired controllers by solving a feasibility problem of LMIs system or a convex optimization problem with LMIs constraints. Based on LMIs, the analysis and synthesis of discrete-time and continuous-time linear positive systems were exploited in Ebihara et al. (2014). By considering quantized and delayed state-feedback control of linear systems with given constant bounds, a LMIs

Download English Version:

https://daneshyari.com/en/article/1725364

Download Persian Version:

https://daneshyari.com/article/1725364

Daneshyari.com