International Journal of Offshore and Polar Engineering (ISSN 1053-5381)

Vol. 16, No. 3, September 2006, pp. 218–227

Towing and Winch Control Strategy for Underwater Vehicles in Sheared Currents

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An efficient approach for planning towing maneuvers for an underwater vehicle via ship and winch control is presented. It is demonstrated that it is possible to generate a towing strategy for a submersible vehicle such that the towed body follows a desired trajectory in the presence of known currents. The approach relies on the fact that the system is differentially flat under certain modeling assumptions; hence, it is possible to determine the required ship motion and winch rate so that the specified trajectory of the submersible is followed. The cable is modeled using a lumped mass approximation, including hydrodynamic drag, buoyancy and added mass effects. In the proposed approach, extensive use is made of spectral collocation methods to compute derivatives of motion. The approach is capable of producing open-loop trajectories in very short computation times, which makes it suitable for real-time computations.

INTRODUCTION

The positioning of deeply towed cables via motion of the surface vessel is a technique often used by sonar platforms. Lemon (2004) recently described the history of towed arrays and some recent developments. In deep water, the distributed effects of inertia and drag forces on the cable make accurate positioning of the vehicle difficult by movement of the surface vessel alone. Major challenges facing such towing maneuvers are the significant time lag between changes in ship motion and the towed-body response, as well as the settling time required for steady towing. Various approaches have been suggested for controlling the ship position to achieve the desired motion of the vehicle. Paul and Soler (1972) considered planar 2-dimensional towing strategies to minimize the time required to move a submersible vehicle to a new position. A lumped parameter model of the cable was used, and it was found that faster maneuvers can be achieved by having the tow ship overshoot the target by a specified amount and then reverse course. Mudie and Ivers (1975) studied the response of a long cable to variations in the ship motion and noted the large time lag in the towed body's response. Chapman (1984) gave detailed results of the behavior of towed cables during circular turns with long scope tow lines. Chapman found a critical turn radius for which the towed body tends to tow inside the ship's circle by a significant factor. This behavior has long been known in towed-aerial systems (Skop and Choo, 1971). Kishore and Ganapathy (1996) also studied the cable dynamics during a loop maneuver with a towed array. Hover (1989, 1993) and Hover and Yoerger (1992) considered the planar control of deeply towed cables using low-order dynamic models of the cable-body system. Relatively good results can be obtained by using such low-order models. Hover and Yoerger (1992) experimentally validated the time-optimal form of the solutions obtained by Paul and Soler (1972). This type of approach has also been very effective for controlling the altitude of the tip of a towed aerial cable system (Williams, 2005). Triantafyllou and Grosenbaugh (1991) designed a closed-loop controller based on linear quadratic gaussian/loop transfer recovery and the Smith controller for systems with time delays. They applied the methodology to position an underwater vehicle through the motion of the surface vessel. Chauvier et al. (1998) considered the optimization of a U-turn maneuver that combined ship maneuvers with cable winch control so as to minimize the time taken to re-establish steady-state towing. Hover (1994) developed an inversion-based approach with input preshaping for computing the ship motion to give the desired motion of the towed fish. This approach was developed in the frequency domain and used constant-length cables and no ocean currents. The effects of unsteady towing conditions on the vibrations of long tow cables has been addressed by Grosenbaugh (1991) and Grosenbaugh et al. (1991) using data from a full-scale experiment. They found that the cable drag coefficient tends to decrease during maneuvers when compared to the steady-state value. From this brief review of the literature, the need is apparent for designing efficient towing strategies for long cables in the presence of varying currents, and that includes cable winch control.

This paper presents an effective algorithm capable of rapidly generating trajectories for towed cable systems. The basic algorithm was originally designed for aerial cable systems by Williams et al. (2005). However, in this paper, it will be shown that this approach is very effective for underwater cable systems. This work presents the fundamental modeling approach for the underwater cable that enables the computation of towed trajectories. The concept of differential flatness will be applied to the system using 2 different parameterizations of the towed-body trajectory. It will be shown that it is possible to generate trajectories for the towed body that pass through multiple waypoints in the presence of sheared ocean currents—a process illustrated conceptually in Fig. 1. The paper is structured as follows: First, a lumped parameter model of the towed-cable system is presented; the procedure used for incorporating pay-in and pay-out of cable in the model is described; the trajectory generation algorithm for 2 different parameterization schemes is presented; numerical results of the algorithm applied to several examples are given; and finally, some conclusions are presented.

3-DIMENSIONAL CABLE MODEL

Cable dynamical models have been presented extensively over the years. Two fundamental approaches have been used with comparable accuracy when compared with experimental results:

Received November 1, 2005; revised manuscript received by the editors April 26, 2006. The original version was submitted directly to the Journal.
KEY WORDS: Cables, towed submersibles, winch control, lumped mass, pseudospectral.