Dynamic Behavior of Towed Cable Systems During Ship Turning Maneuvers

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Award Numbers: N00014-04-1-0030 and N00014-04-1-0261

LONG-TERM GOALS

The long-term goal is to develop a framework for controlling towed vehicles through a combination of ship maneuvers and active control devices on the towed vehicle. Typical usage of a towed reconnaissance system involves towing a vehicle with acoustic and optical sensors back and forth over a search area along parallel track lines. At the end of each track line, the vehicle executes a 180-degree turn so that it ends up on a new track line and at a specified towing depth. In some cases, the towing depth is varied with time depending on the ocean bottom topography. How best to optimize the towing strategy for a particular set of track lines is still an open question.

OBJECTIVES

Our objective is to analyze the dynamics of a towed cable-vehicle system during ship turning maneuvers. This work will extend the analysis of Chapman (1984) to include transient effects due to currents, waves, and the inertia of the tow-cable system. We expect that a complete parametric analysis will lead to the redefinition of the critical turn radius and provide a mapping of stability boundaries between large-radius turn behavior (where the configuration is a perturbation of the straight-line towing solution) and small-radius turn behavior (where the cable configuration undergoes a rapid collapse with an accompanying rapid increase in the tension). The parametric analysis will include the effects of time varying vortex-induced vibrations and active control of the towed vehicle.

APPROACH

The research will be carried out using numerical simulation and full-scale experiments. The simulations will be performed using our WHOI Cable software for calculating the dynamics of moored and towed systems (Gobat & Grosenbaugh, 2000, 2005). The software uses an implicit finite difference, time domain simulation that is built around a mathematical model of cable dynamics. The cable model is fully three-dimensional and includes the effects of torsion, bending, and geometric and material nonlinearities. A generalized-α method that allows for the introduction of numerical dissipation is used for the temporal integration (Gobat & Grosenbaugh, 2001). This replaces the box-method scheme, which is used in Ablow & Schechter (1983) and which can lead to Crank-Nicholson errors in the solution. The initial set of simulations will be carried out with similar assumptions regarding the dynamics of the tow ship and towed vehicle as used by Chapman (1984). That is the tow ship is assumed to be unaffected by the cable dynamics, and the towed vehicle's weight, inertia and drag are assumed to act at the end point of the tow cable.

More advanced simulations will incorporate a variable drag coefficient that is calculated as part of the solution. Over the last decade, research has shown that the drag coefficient can vary both temporally and spatially (along the length of the cable) due to vortex-induced vibrations caused by shear in the normal current profile (Grosenbaugh *et al.*, 1991). During ship turning, there will be a large effective vertical shear current due to the bottom of the cable moving through the water at a reduced speed to that of the surface ship though now the motion is three dimensional. The development over time (while the ship is turning) of this effective three-dimensional shear profile will greatly impact the overall configuration of the tow cable. If we could calculate the actual distribution of the normal drag coefficient, as part of the overall dynamic solution of the towing/maneuvering problem, we could greatly improve the accuracy of the dynamic analysis. To do this, we will collaborate with Prof. Michael Triantafyllou of MIT to integrate his VIVA software (Triantafyllou *et al.*, 1998) for predicting vortex-induced vibrations into our numerical model for cable dynamics. Once this is completed, we will perform a complete parametric study involving turning maneuvers of different radii and different speeds, cables of different length and weight, vehicles of different mass and buoyancy, and different wave and current conditions.

Verification of the combined WHOI Cable and VIVA code will be made using data gathered during full-scale experiments involving turning maneuvers of a towed vehicle. Ship and vehicle trajectory will be measured using GPS and an acoustic tracking system, respectively. Cable vibrations will be measured by, attaching to the cable, accelerometer packages similar to but much smaller than those used by Grosenbaugh *et al.* (1991). Drag coefficients will be inferred from the vibration amplitudes. The experimental maneuvers will include 180-degree turns, 360-degree turns, and multi-circular turns that allow the system to approach the steady-state turning condition.

An important set of simulations will be carried out to examine, specifically, the effect of different towed vehicle control actions on the dynamic behavior of the overall towed system during turning maneuvers. For this, we will modify our software to include the dynamics of the towed vehicle through the boundary conditions of the cable equations. The control actions themselves will be implemented using a PID controller. Even though this is a linear controller, by its introduction as a time-varying boundary condition, it will introduce nonlinearities, which could dramatically change the overall stability properties of the towed system during turning.

WORK COMPLETED

We compared *WHOI Cable* simulations with results from other studies involving towed arrays (Ablow and Schecter, 1983). The towed array results were incorporated into a manuscript about the *WHOI Cable* numerical scheme, which was submitted this year and is now in press (Gobat and Grosenbaugh, 2005). We are preparing a new manuscript on simulation results of towed vehicles undergoing circular maneuvers and the comparison with previous studies (Chapman, 1984). We continue to work on incorporating *VIVA* software into *WHOI Cable* so that we can calculate the normal drag coefficient as a function of instantaneous vibration amplitude. We performed a comparative study on the use of thruster control mounted on a towed vehicle undergoing two-dimensional maneuvers. These results were published in Grosenbaugh and Bowen (2005). We presented a workshop on the use of the *WHOI Cable* software with emphasis on towed sonar arrays to engineers at SACLANT Undersea Research Centre in October 2004.

RESULTS

We simulated a maneuver of a depressor weight and ROV being towed by a 4000 m long cable to a new location 400 m away from a previous location, holding position within 20 m of the new location for 10 minutes, and then returning to within 1 m of the original position. Using passive ship movement, the maneuver took almost 160 minutes to accomplish (Fig. 1). To improve performance, we examined two alternate strategies. One strategy involved the ship overshooting its estimated end point on the sea surface before settling back just as the vehicle was approaching its actual end point on the ocean floor. Without doing any optimization, we were able to use this ship-overshoot strategy to reduce the time of the maneuver to about 100 minutes (Fig. 2). Finally, we simulated the action of a thruster on the vehicle that is used in conjunction with ship movement. This control strategy reduced the time of the maneuver to about 65 minutes, again with no optimization (Fig. 3). These results indicate that active control through a combination of actuation at the top and bottom of a tow cable could greatly improve the performance of towed oceanographic survey systems (see Grosenbaugh and Bowen, 2005).

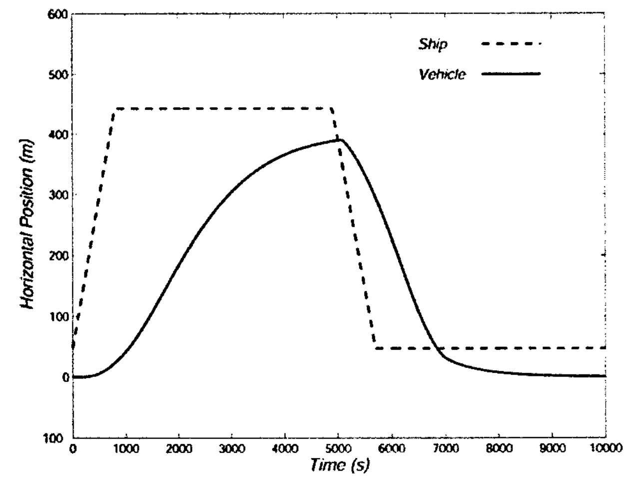

Fig. 1. Horizontal position of ship and vehicle during basic maneuver.

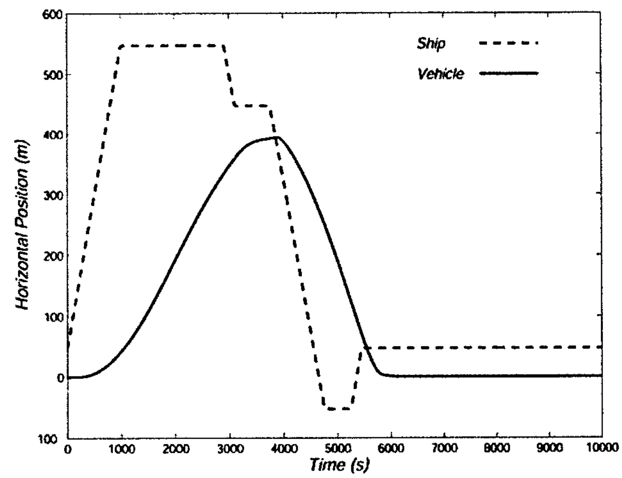

Fig. 2. Horizontal position of ship and vehicle during overshoot maneuver.

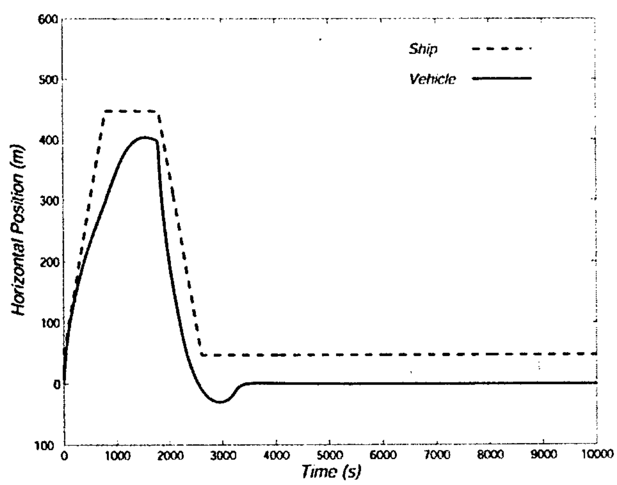

Fig. 3. Horizontal position of ship and vehicle during vehicle thruster maneuver.

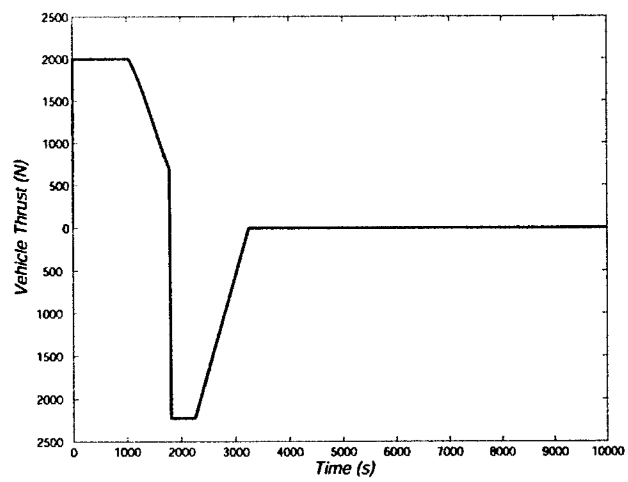

Figure 4. Vehicle thrust during maneuver shown in Fig. 3.

IMPACT/APPLICATIONS

Our research has direct applications to many of the towed vehicle systems used in the Navy and the oceanographic community. An example of this, is the Remote Minehunting System (RMS), which is a Navy system being developed by Lockheed Martin with program oversight by NAVSEA (PMS490). Our results will apply equally well to the towing of variable depth sonars by airborne mine reconnaissance helicopters (e.g. towing of the AN/AQS-20 by the MH-53E helicopter and the prototype AN/AQS-20X by the CH-60S helicopter) where the stability issues may be even more important due to the large length of cable suspended in the air, which experiences very little damping. We are also working on applications to submarine towed arrays, whose configuration can be affected by internal waves such as in the South China Sea.

TRANSITIONS

We continue to make our *WHOI Cable* software available to academic institutes, government research labs, and government contractors at no cost through our FTP site. At present, nearly 120 different individuals, including a number of engineers working at Navy Labs and on Navy funded R&D projects, use *WHOI Cable* for mooring and tow cable analysis.

RELATED PROJECTS

WHOI Cable is playing a large role in two NSF engineering development projects. The first is in support of the Ocean Observatory Initiative, which is a Major Equipment Acquisition to deploy a network of permanent and semi-permanent ocean laboratories around the world. The network will be connected in real time by submarine cables and surface moorings. Our role is in the design and development of a new low-modulus electro-optical-mechanical mooring cable. We are working with engineers at Monterey Bay Aquarium Research Institute on this project. The second project involves the development of the HROV that is self-powered but tethered to a ship by a single optical fiber that deploys same type of cannisters that are used with Navy torpedos. The vehicle has applications for deep missions (depths up to 11,000 m) and missions under the Artic ice cap. Our role involves the analysis of the cable handling system that controls payout. We are working with engineers at SPAWAR on this project.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From – To)*
13/10/2005	Technical Report	15 February - 31 December 2004

4. TITLE AND SUBTITLE

Dynamic Behavior of Towed Cable Systems During Ship Turning Maneuvers

5a. CONTRACT NUMBERS
N00014-04-1-0030
N00014-04-1-0261

5b. GRANT NUMBER
N00014-04-1-0030
N00014-04-1-0261

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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Woods Hole, MA 02543

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING ACRONYM(S)

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19 b. TELEPHONE NUMBER *(Include are code)*