DSTA 2021
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16th INTERNATIONAL CONFERENCE
Dynamical Systems – Theory and Applications
December 6-9, 2021, On-line

Dynamics and control of a two-ship ensemble

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Abstract: The current study represents a fundamental step toward automating the towing mission of disabled vessels. It deals with the control of transient planar dynamics for a two-ship ensemble connected by a massless cable. This is a multibody structure whose components are coupled by non-holonomic inequality constraints. The control strategy is designed by exploiting the essential temporal scale difference between relative tugboat-ship dynamics induced by the constraints and the relatively slow motion of the mass center of the two-ship ensemble. The proposed control strategy reduces the controller's susceptibility to sharp variations in the towline tension. The results demonstrate the viability of the controller and illustrate its robustness to environmental disturbances.

Keywords: multibody system, autonomous towing, interconnected vessels control

1. Introduction

Emergency towing vessels (ETVs) and harbour tugs are relied on to rescue wrecked or disabled ships in bad weather on the open seas by towing them to a safe location [1,2]. This challenging problem involves the dynamics and control of an under-actuated multi-body system subjected to non-holonomic inequality constraints. The control variables in the two-ship ensemble are restricted to the propeller thrust and angular displacement of the leading ship. The control actions are transmitted to the disabled ship through the cable force. A schematic of the physical system is depicted in Fig. 1.

2. Model of the Two-Ship Ensemble and Controller Design

An ensemble of two ships connected by a massless towline with one vessel being totally disabled has been considered in this study. Three-degree of freedom models were developed for the tugboat and the towed ship to describe their motions in the horizontal plane. The effects of unilateral, non-holonomic, inequality constraints, induced by the limits on the distance between the points on the marine vessels where the cable extremities are attached, are represented by a specific potential energy function having a shallow potential well when the cable is not taut. However, this function tends to increase exponentially as the cable is stretched beyond its original length, which emulates the strain energy stored in a cable under tension. The equations of motion of the two-ship ensemble were derived by using the Lagrange principle. The external forces and moments applied on both ships are induced by drag and wave excitations along with the control force and moment on the tugboat. Empirical formulations were incorporated to account for the effects of wave excitations, wind and sea current drag forces and moments. The control scheme is designed by exploiting the essential temporal scale difference between the relative tugboat-ship dynamics induced by the constraints and the relatively slow motion of the mass center of the two-ship ensemble. It is designed to maintain a

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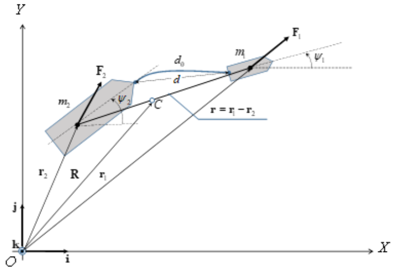

Fig. 1. A disabled ship towed by an ASV through an ideal flexible cable.

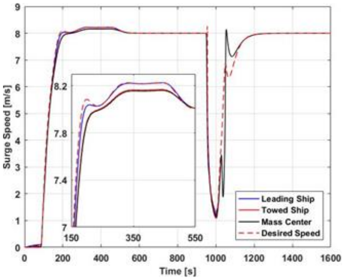

Fig. 2. Surge speeds in the presence of both wave excitations and sea current disturbances.

prescribed heading angle and surge speed for the mass center of the two-ship ensemble. The rationale is to reduce the controller's susceptibility to sharp variations in the towline tension force. Note that the dynamics of the leading ship are directly and adversely impacted by large spikes in the cable tension normally occurring during transient periods. The challenge in designing the controller stems from the fact that the disabled ship becomes uncontrollable whenever the cable seize to be taut. The controller of the tug has to simultaneously perform a tracking task while preserving the controllability of the system by ensuring that the cable is always taut. This has to be done without producing large impulsive tension force in the cable that could result in the ships moving towards each other with the possibility of a collision. Thus, the propeller thrust control signal of the leading ship is defined as $P_1(t) = P_1^c(t)[1 - w(t)] + P_1^T(t)w(t)$ where P_1^c is responsible for keeping the cable taut, P_1^T is the trajectory tracking control signal and w is a weighting factor ensuring a smooth transition between P_1^c and P_1^T. The PID control scheme was implemented in the design of both propeller controller and heading controller of the leading ship. Note that the desired surge speed and heading angle of the leading ship were computed to yield the desired surge speed and heading angle of the mass center of the two-ship ensemble.

3. Results and Discussion

Figure 2 demonstrate the viability of the proposed controller and illustrates its disturbance rejection characteristic to wave excitations and sea current disturbances. The latter varied in magnitudes and applied at different times on the leading and disabled vessels. The disturbance on the leading ship led to a zero tension in the towline causing the controller to lose its controllability over the disabled ship. Also, the two vessels exhibited out-of-phase heading angles during this phase of the maneuver. However, within a short period of time, the controller regained its controllability over the disabled ship, stabilized the cable length and forced the two-ship ensemble to once again behave almost like a single rigid body. The disturbance on the disabled ship had an opposite effect on the towline. It served to drastically increase the cable tension that enhanced the capability of the two-ship ensemble to preserve its behavior almost like a single rigid body under severe transient conditions.

References

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