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Real-time simulation of cable pay-out and reel-in with towed fishing gears

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ABSTRACT

Achieving real-time simulation of fast cable pay-out and reel-in manoeuvres with towed fishing gears is a challenging task. This work presents two new simulation methods based on simplified cable models for this kind of application. First, three numerical techniques are proposed to enhance a classical spring-based cable model, increasing its computational efficiency in manoeuvres that involve reeling the cable around a winch drum. Second, the development of an efficient multibody modelling approach based on natural coordinates is reported. The performance of these methods was assessed with two realistic examples. The numerical experiments involved different values of cable axial stiffness and spatial discretization levels, since these parameters were found to have a major impact on computational efficiency. The proposed methods achieved real-time performance in the simulation of systems modelled with up to a few thousand variables. Each modelling approach has advantages and limitations that must be considered when addressing a given application.

1. Introduction

Towed fishing gears such as trawls and seines are responsible for 70% of the world fish catch (Watson et al., 2004). These gears are complex mechanical structures mainly composed of netting and cables. Increasing concerns about environmental impact and energy efficiency in the fishing industry are driving the development of numerical models especially suited for these kinds of assemblies, aiming at designing new gears with improved catch capability and selectivity and reduced environmental impact (Khaled et al., 2012, 2013; Lee et al., 2011; Takagi et al., 2007).

Detailed information about the design and classification of fishing gears can be found in Nédélec and Prado (1990). Fig. 1 shows a representation of a trawl, the predominant type of towed fishing gear. It consists of a flexible cone-shaped net that is pulled through the water by two long cables (0.5–3 km) attached to winches on a fishing trawler. Towing speed ranges from 0.5 to 3.5 m/s. The net is made up of polygonal netting panels sewn to each other and is connected to other elements to ensure its proper deployment and buoyancy. The vertical spread of the net is provided by floats and weights placed on its upper and lower edges, respectively. The horizontal spread is generated by lateral hydrodynamic forces on the doors. Trawl doors weigh between 0.5 and 5 tons and their surface area ranges from 2 to 12 m^2, depending on the net size. Midwater trawls work without contacting the seabed, while in bottom trawls the lower part of the net is in contact with the sea floor.

A fishing haul has three stages: shooting, towing, and heaving. Shooting consists of paying out the cables at constant speed, around 1–2 m/s, while the trawler sails until they achieve the desired length and the gear gets completely deployed. During towing, the winch control system regulates the cable length and tension to keep them within their admissible ranges. The cable tension during this operation can reach up to several dozen tons. State-of-the-art control systems also attempt to maintain the symmetry of the gear, which can be affected by ocean currents. To achieve this, they combine information from different sensors on the gear and trawler and operate the winch to let out or reel in the cables at high rates. Modern electric winches can reach reeling velocities of up to 250 m/min in less than 1 s, starting from rest. The towing stage can last from 15 min to several hours. During heaving, the cables are reeled in; the control system keeps their tension under a maximum admissible value to avoid damaging the gear.

Efforts to simulate towed fishing gears have mainly focused on the calculation of the static equilibrium shape of the gear subjected to a constant water flow, although methods to deal with dynamic equilibrium can be found in the literature as well. Authors have proposed different methods to discretize the net and solve the resulting equations (Le Dret et al., 2004; Lee et al., 2005; O'Neill, 1997; de la Prada and González, 2016; Priour, 1999; Shimizu et al., 2004), experimental procedures to measure elastic properties of netting (de la Prada and González, 2015; Sala et al., 2004, 2007), models for hydrodynamic forces on the gear (Bi et al., 2014; Gansel et al., 2012), and methods to optimize gear design (Khaled et al., 2013; Priour, 2009).

A more challenging application is the simulation of towing in order to design and evaluate new concepts of gear control (Reite, 2006). This

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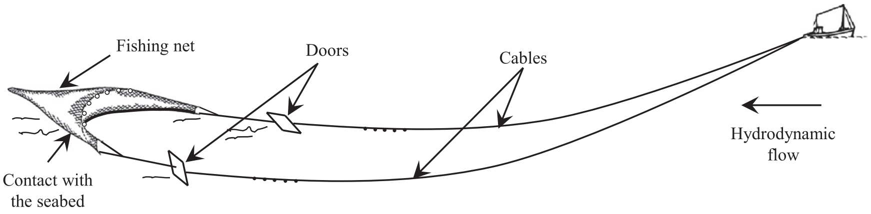

Fig. 1. Components of a fishing trawl.

kind of co-simulation uses a dynamic model of the fishing gear as plant model inside the simulation of the control system. In some cases, these simulations are used in human-in-the-loop setups, i.e., applications that require real-time user interaction with the control system. Efficient dynamic formulations are then required to deal with the fast pay-out and reel-in motion of the cables in real-time.

Cable mechanics has been the subject of intensive studies during the last five decades. State-of-the-art programs for the analysis of submerged cables use a spatial discretization of the continuous partial differential equations of the cable based on the finite element method (Buckham et al., 2004) or finite differences (Gobat and Grosenbaugh, 2006). These approaches include the effect of all kinds of geometric and material nonlinearities and their robustness allows one to simulate constant-length towing cables with step-sizes of seconds (Gobat and Grosenbaugh, 2006). However, their computational overhead prevents their use in some applications that require real-time computations such as the above-mentioned human-in-the-loop simulation of gear control systems, in which fast dynamics demands the use of small integration step-sizes (Johansen, 2007).

An approach to achieve high computational efficiency is to use simplified cable models at the expense of neglecting some geometric and material nonlinearities, such as bending or torsional stiffness and cross section reduction due to axial strain (Park et al., 2003). In practice, the validity of these models is determined by the characteristics of the application under study. In fishing assemblies, the range of cable tensions and moderate torsion and curvature radius make these simplifications acceptable (Priour and de la Prada, 2015). Often, simplified models discretize the cable as a sequence of segments connected by joints that allow them to rotate with respect to each other; bending stiffness can be modelled with torsion springs between bars (Fritzkowski and Kamiński, 2010). These segments can be flexible or rigid along their longitudinal axis, or a combination of both (Fritzkowski and Kamiński, 2009). Linear spring models (Lee et al., 2005; Priour, 2009) are instances of the first kind; structural damping can be included in these flexible elements as well (Buckham et al., 2003; Yao et al., 2016). These models have been demonstrated to work well in the dynamic simulation of towed gears, and they show good agreement with experimental results (Priour and de la Prada, 2015; Takagi et al., 2004). If the cable is discretized as a chain of rigid links, then multibody formulations can be employed to solve the dynamics of the resulting model. This method neglects the axial flexibility of the cable, which can be a valid assumption for stiff cables. The rope model described in Fritzkowski and Kamiński (2010) is a 2D example of this second approach; only a few publications exist that use 3D multibody modelling in practical marine applications (Kamman and Huston, 2001), especially in the context of towed fishing gears (Madsen et al., 2015).

Even with simplified cable models, real-time simulation of let-out and reel-in operations remains an exacting task. The quick motion of the system, the changes in the free length of the cable, and their effect on cable tension have to be considered and correctly dealt with. In practice, carrying out the integration with step-sizes in the range of milliseconds is mandatory. Moreover, the accurate modelling of cable behaviour, e.g., determining the contact region between the cable and the seabed, demands the use of discretizations with a relatively large number of elements, ranging from one hundred to a few thousands. Numerical methods able to perform real-time integration of the resulting dynamics equations while keeping the simulation stable have not been reported yet in the literature.

The present paper puts forward efficient computational methods for the real-time simulation of manoeuvres with submerged cables and fishing gears. The main scientific contributions of this work can be summarized as follows. First, it introduces three numerical improvement approaches to enhance the performance of classical spring-based cable models during reel-in and reel-out manoeuvres. These alleviate the time-scale reduction caused by the shortening of cable elements introduced when changes in cable length are represented with variable-size segments. Second, it reports a new multibody model of the cable, based on natural coordinates, which constitutes an efficient way to formulate the system dynamics, alternative to using spring models. The system dynamics equations were solved making use of augmented Lagrangian and Hamiltonian formulations, whose application to real-time cable dynamics had not been reported yet, and integrated with simple time-stepping routines. Third, the efficiency of the multibody methodology in the simulation of reel-in and reel-out motion was further improved via an acceleration-level penalization of the dynamics of the wound cable segments. The use of these techniques made it possible to achieve real-time simulation of let-out and reel-in manoeuvres with towed fishing gears, using cable discretizations comprising up to one thousand segments.

2. System modelling

Two alternative approaches to cable modelling are introduced in this section. The first one is a linear spring model and the second uses a multibody discretization.

2.1. Linear spring model of the cable

In the context of fishing operations, cables are traditionally modelled as a series of point masses connected by linear spring elements (Lee et al., 2005; Takagi et al., 2004; Priour and de la Prada, 2015) as shown in Fig. 2. This approach assumes that: (a) the effect of the bending stiffness of the cable is negligible compared to its axial stiffness; (b) the contribution of the rotational inertia of the cable to the dynamics is not significant; and (c) the structural damping of the cable is less relevant than the one introduced by hydrodynamic forces. These assumptions are valid in the context of towed fishing gears,

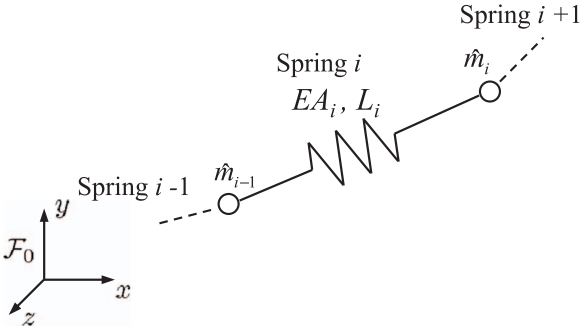

Fig. 2. Discretization of a cable into a chain of mass–spring elements.