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Multibody dynamic analysis of a heavy load suspended by a floating crane with constraint-based wire rope

Seung-Ho Ham [a], Myung-Il Roh [b,*], Hyewon Lee [a], Sol Ha [c]

[a] Department of Naval Architecture and Ocean Engineering, Seoul National University, Seoul 08826, Republic of Korea
[b] Department of the Naval Architecture and Ocean Engineering, and Research Institute of Marine Systems Engineering, Seoul National University, Seoul 08826, Republic of Korea
[c] Department of Ocean Engineering, Mokpo National University, Muan-gun 58554, Republic of Korea

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ABSTRACT

In this study, we derived a Discrete Euler–Lagrange (DEL) equation to represent the motion of a multibody system, in which many bodies are connected physically by joints or wire ropes. By discretizing and re-formulating the traditional Euler–Lagrange equation, we obtained a discrete time integrator, called the Stömer–Verlet method. Similarly, we discretized the equations of constraints of joints and wire ropes by the midpoint rule. Then, we adapted regularization and stabilization methods, to overcome numerical instability and the stiffness problem.

The DEL equation can be formulated automatically, by defining the equations of joint constraints and their derivatives. In addition, the stretching of the wire rope is mathematically modeled as constraints for stability. To apply the DEL equation to a floating vessel, hydrostatic and hydrodynamic forces are considered as external forces.

We applied the DEL equation to a mass–spring system with the large spring coefficient. And we tested a spring pendulum modeled by a constraint-based wire rope. Despite the large spring coefficient, the DEL equation with the constraint-based wire rope shows relatively stable motion. We tested the automatic formulation by three-dimensional multiple pendulums. Finally, we simulated a floating crane and a heavy load connected by constraint-based wire rope, based on set of regular waves with different wave heights, directions and periods.

1. Introduction

1.1. Research background

As new lifting methods are tried in the shipbuilding area, it becomes more difficult to predict the risks of the lifting operation. Moreover, as the weight and size of blocks and modules of offshore projects increase, it is not easy for production planning engineers to prove that the lifting plan is perfectly safe, and that there is no reason for disqualification. In this situation, dynamic analysis is required to manage the potential risk in advance. Fig. 1 shows typical examples of block lifting by floating cranes in shipbuilding production.

This study mainly focused on the dynamic analysis of block lifting using floating cranes. Although dynamic analysis is basically based on Newton's 2nd law of motion, it is not easy to apply this law directly to the targeted bodies, because each body is connected to one or more other bodies by wire ropes and joints. These are termed constraints, and generate constraint forces on each other. Therefore, an appropriate formulation should be chosen to solve the equations of motion including constraint forces. Moreover, floating cranes, for which motions are induced by seawater, and multiple wire ropes should be simulated in a reasonable manner, as Fig. 1 shows. There are several requirements to consider when choosing the formulation.

(1) Stability: During simulation, we adopt a numerical integration method, because of the nonlinearity of the equation. Stability means that the result should not shrink or diverge during time integration. This is the most important factor for choosing the formulation.
(2) Performance: The simulation should run in real time at a fixed time step. This means that a relatively fast integration method should be chosen, with low computational cost.
(3) Automation: The equations of motion should be automatically formulated, having regard to the constraints and external forces.
(4) Wire rope: Wire ropes used to lift blocks generally have a very large spring coefficient. This causes a stiffness problem, which

* Corresponding author. Tel.: +82 2 880 7328.
E-mail address: miroh@snu.ac.kr (M.-I. Roh).

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Fig. 1. Typical examples of block lifting by using floating cranes in shipbuilding production.

makes the integration unstable. For stable simulation, wire ropes should be carefully modeled.

(5) Floating vessel: The motion of a floating vessel is influenced by two forces. One is the hydrostatic force, which is the same as the displaced water weight; and the other is the hydrodynamic force, which is exerted by waves.

1.2. Related studies

1.2.1. Studies on floating crane simulation

Ellermann et al. (2002) considered the motions of a floating crane and cargo in a two-dimensional plane, which means that the floating crane has only three degrees of freedom. They considered the cargo as a pendulum. However, in reality, the total degrees of freedom of the floating crane and the cargo are up to 12. Furthermore, the tension of the wire rope could not be calculated in their study, because the wire rope was modeled as a pendulum.

Cha (2008) and Cha et al. (2010a) adopted multibody dynamics to formulate the motion of the floating crane and the heavy cargo with full degrees of freedom. To calculate the tension of wire ropes between the floating crane and the cargo, the wire ropes were modeled as incompressible springs. However, they manually derived the equations of motion. Therefore if the models or constraints change, the equations should be derived again. This takes much effort to obtain the final form of the equations, because the position vectors are differentiated twice.

Cha et al. (2010b) used a topological modeling approach to automatically formulate the equations of motion, by considering the connectivity between two bodies. This idea is to find the velocity transformation matrix from the multiplication of separate sub-matrices, such as the transformation matrix, connectivity matrix and joint characteristic matrix. However, this formulation does not guarantee the stability of the solution induced by a large spring coefficient. To avoid this problem, they use relatively small spring coefficients, compared to the coefficient of real wire rope.

1.2.2. Studies on dynamic analysis formulation

A system in which joints or wire ropes physically connect many bodies is called a multibody system. Many formulations have been suggested to describe the motion of multibody systems.

Shabana (1994) explained two kinds of formulation. One is the augmented formulation, which maintains the body coordinates, and introduces Lagrange multipliers to contain the constraint forces. The other is the embedding technique, which allows elimination of the dependent coordinates and constraint forces.

Meanwhile, there is one more formulation, named the Euler–Lagrange equation, which is derived from analytic methods. By using the Euler–Lagrange equation, the constraint forces can be neglected in the equation. The Euler–Lagrange equation looks simple compared to the augmented formulation and the embedding technique, because it uses velocity, rather than acceleration. However, it contains derivatives, which make it difficult to automatically obtain the equations of motion. Haug (1992) even observed that the Euler–Lagrange equation was not practical.

To overcome this limitation of the Euler–Lagrange equation, many studies, including Wendlandt and Marsden (1997), Marsden and West (2001), and Lew (2003), adopted the finite differential method, which changed the ordinary differential equation to the algebraic equation by discretization. From the discretization process, the discrete Euler–Lagrange (DEL) equation was obtained.

However, if there are constraints, such as joints and wire ropes, the equations of motion usually become an index-3 system, which needs an index reduction process. Unfortunately, the numerical solution of the index-reduced system was not satisfied with the original constraints. Bendtsen and Thomsen (1999) reported that during numerical integration, index reduction induced a drift-off, and an initial value problem. Therefore, Baumgarte (1972) and Eich and Hanke (1995) suggested regularization methods that add penalty terms to the original constraint equations.

Even though the regularization term is inserted in the equation, the numerical integration still can be unstable. Therefore, Yoshimura and Yoshida (2010) introduced a stabilization method that