DYNAMIC RESPONSE ANALYSIS OF MULTIBODY SYSTEM IN DISCRETE EVENT SIMULATION

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Abstract: There are several kinds of mechanical systems that are under event-triggered conditions. For the dynamic analysis of such mechanical systems, a simulation program that can generate equations of motion for mutibody systems in the discrete-event simulation framework was developed. For complex multibody systems, a dynamics kernel was developed to generate the equations of motion for multibody systems based on multibody dynamics. To generate the equations of motion, the recursive formulation method was used. Using the developed dynamics kernel, the dynamic responses of multibody systems can be carried out under continuous conditions. The general multibody dynamics kernel, however, cannot deal with discontinuous-state variables and event-triggered conditions. The multibody dynamics kernel, therefore, was integrated into the discrete-event simulation program to deal with multibody systems in discontinuous environments. The discrete-event simulation program was developed based on the discrete-event system specification (DEVS) formalism, which is a modular and hierarchical formalism for analyzing systems under event-triggered conditions.

1 INTRODUCTION

In many engineering fields, the need for accurate dynamic-response analysis using a simulation tool is increasing. Especially in the shipbuilding industry, there are various types of mechanical systems that have to be analysed. Fig. 1 shows three examples of such mechanical systems. Fig. 1(a) shows a goliath crane, which is used to lift and transport heavy loads and important facilities in shipyards. Fig. 1(b) shows a floating crane, whose capacity is usually greater than that of the goliath crane. As shown in the figure, unlike the goliath crane, the floating crane is operated on the sea. Fig. 1(c) shows floating offshore wind turbines. All of these facilities are mechanical systems that have to be analysed in their dynamic aspects for accurate design.

The mechanical systems shown in Fig. 1 can be considered as multibody systems, which are collections of interconnected rigid bodies, consistent with various types of joints that limit the relative motion of pairs of bodies. Planners of shipbuilding process, therefore, use commercial programs when they receive requests for dynamic-response analysis. These methods, however, have some limitations. As the commercial programs for dynamic analysis are

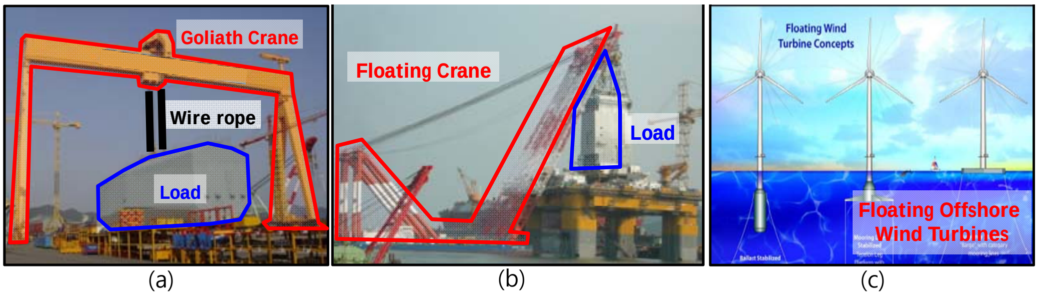

Figure 1: Various types of mechanical systems in the shipbuilding industry: (a) goliath crane; (b) floating crane; and (c) floating offshore wind turbines.

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usually developed for general purposes, they may not be suitable for the various requirements of process planning in shipbuilding.

For instance, the block-lifting and transport process, which is carried out by a goliath or floating crane, consists of several discontinuous stages, such as hoisting-up, transport, and hoisting-down. Meanwhile, most of the commercial programs for multibody dynamic analysis cannot deal with discontinuous-state variables as well as event- and state-triggered conditions.

Therefore, the dynamics kernel was developed, which can generate the equations of motion of multibody systems for the accurate analysis of dynamic systems. To deal with a multibody system in a discontinuous environment, the multibody dynamics kernel was integrated into the discrete-event simulation program, which was developed based on the discrete-event system specification (DEVS) formalism. DEVS formalism is a modular and hierarchical formalism for modelling and analyzing systems under event-triggered conditions, which are described by discontinuous-state variables.

2 RELATED WORKS

ADAMS (Automatic Dynamic Analysis of Mechanical Systems) is a software system consisting of a number of integrated programs that help an engineer in performing three-dimensional kinematic and dynamic analyses of mechanical systems (Orlandea et al., 1977, Schiehlen, 1990). ADAMS generates equations of motion for multibody systems using augmented formulation. The user can define any multibody system composed of several bodies that are interconnected by joints. ADAMS supplies various types of joints, such as fixed, revolute, and spherical joints. Various external forces can also be applied to multibody systems, but ADAMS cannot handle discontinuous-state variables as well as event- and state-triggered conditions.

ODE (Open Dynamics Engine) is an open-source library for simulating multibody dynamics (Smith, 2006). Similar to ADAMS, ODE derives equations of motion for multibody systems using augmented formulation. ODE cannot handle discontinuous-state variables as well as event- and state-triggered conditions.

RecurDyn is a three-dimensional simulation software that combines dynamic-response and finite-element analysis tools for multibody systems. It is two to 20 times faster than other dynamic solutions because of its advanced, fully recursive formulation. Various joints and external forces can also be applied to multibody systems, but RecurDyn cannot handle discontinuous-state variables as well as event- and state-triggered conditions.

On the other hand, Praehofer, Zeigler, et al. (1990, 2000) proposed a modelling and simulation method that can handle simulation models of discrete events and times. They also developed a simulation framework based on the proposed method. In the case of discrete-event simulation, the operation of a simulation system is represented as a chronological sequence of events. Process or material flow simulation systems and the like are included in the category of discrete-event simulation. On the other hand, in the case of discrete-time simulation, the operation of a simulation system is represented as the progress of time. State changes occur only at discrete-time instants. Dynamic simulation systems and the like are included in the category of discrete-time simulation, but the developed simulation framework focuses only on the material flow simulation system of a workshop. Thus, it was difficult for it to be applied to a large factory such as a shipyard, and it was hard to use the existing design and production information for the simulation.

Many researches related to mutibody dynamic analysis and discrete-event simulation have been conducted, but they had some limitations in their application to process planning in shipyards, as mentioned earlier. To overcome these limitations, a dynamics kernel that can automatically generate the equations of motion of multibody systems was developed and was integrated into the discrete-event simulation program.

3 DEVELOPMENT OF A MULTIBODY DYNAMICS KERNEL FOR DYNAMIC ANALYSIS

The facilities in shipyards, as shown in Fig. 1, are multibody systems. For the modelling and dynamic analysis of these multibody systems, a dynamics kernel was developed. In this section, the coordinate system and the properties of the rigid body will be explained. The three formulations (augmented, embedding, and recursive formulations) for the derivation of equations of motion will be presented.

3.1 Construction of the Kinematics of a Multibody System

3.1.1 Reference Frames and Properties of the Rigid Bodies

To model the multibody system, the position and orientation of the rigid bodies must be defined with respect to the inertial reference frame. Because the body fixed frames represent the position and orientation of each rigid body, such frames should be defined for every rigid body.

For each rigid body, moreover, it is necessary to define the mass, mass moment of inertia about three axes of the body fixed frame, and position of the center of mass with respect to the body fixed frame.

3.1.2 Derivation of Equations of Motion by using Recursive Formulation

The process of the derivation of equations of motion for multibody systems with a large number of bodies is difficult because many vectors and matrix manipulations are involved. For this reason, various formulations for the derivation of equations of motion have been developed. In this study, recursive formulation was used to derive equations of motion because its computational efficiency is better than that of the other formulations, such as the augmented and embedding formulations.

1) Augmented formulation

One of the formulations for the derivation of equations of motion is augmented formulation, which is represented by the following equation:

$$\begin{bmatrix} \mathbf{M} & \mathbf{C}_\mathbf{r}^T \\ \mathbf{C}_\mathbf{r} & 0 \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{r}} \\ \boldsymbol{\lambda} \end{bmatrix} = \begin{bmatrix} \mathbf{F}^e \\ \mathbf{F}^d \end{bmatrix}$$

Constraint: $\mathbf{C}(\mathbf{r}, t) = 0$

Differentiation twice: $\mathbf{C}_\mathbf{r}\ddot{\mathbf{r}} + (\mathbf{C}_\mathbf{r}\dot{\mathbf{r}})_\mathbf{r}\dot{\mathbf{r}} = 0$, where $(\mathbf{C}_\mathbf{r}\dot{\mathbf{r}})_\mathbf{r}\dot{\mathbf{r}} = -\mathbf{F}^d$

$\boldsymbol{\lambda}$: Lagrange Multiplier

$\mathbf{M}$: Mass and mass moment of inertia
$\mathbf{r}$: Absolute Coordinates
$\mathbf{C}_\mathbf{r}$: Differentiation $\mathbf{C}$ with respect to $\mathbf{r}$
$\mathbf{F}^e$: External force

Figure 2: Augmented formulation for the derivation of equations of motion.

2) Embedding formulation

Another formulation for the derivation of equations of motion is embedding formulation, which is represented by the following equation. As the dependent coordinates are eliminates in the equations of motion, the constraint equations are not explicitly shown.

$$\tilde{\mathbf{M}}\ddot{\mathbf{q}} + \tilde{\mathbf{k}}(\mathbf{q}, \dot{\mathbf{q}}) = \tilde{\mathbf{F}}^e(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}})$$

, where $\tilde{\mathbf{M}} = \mathbf{J}^T\mathbf{M}\mathbf{J}$, $\tilde{\mathbf{k}} = \mathbf{J}^T\mathbf{M}\dot{\mathbf{J}}\dot{\mathbf{q}}$, $\tilde{\mathbf{F}}^e = \mathbf{J}^T\mathbf{F}^e$

$\mathbf{q}$: Generalized coordinate
$\mathbf{M}$: Mass and mass moment of inertia
$\mathbf{F}^e$: External force
$\mathbf{J}$: Velocity transformation matrix, $\dot{\mathbf{r}} = \mathbf{J}\dot{\mathbf{q}}$

Figure 3: Embedding formulation for the derivation of equations of motion.

where is the mass and the mass moment of inertia matrix and is the Coriolis and centrifugal matrix.

3) Recursive formulation

$$\mathbf{v}_i = \mathbf{v}_{i-1} + \mathbf{S}_i\dot{q}_i \quad \cdots\cdots (1)$$
$$\mathbf{a}_i = \mathbf{a}_{i-1} + \mathbf{S}_i\ddot{q}_i + \dot{\mathbf{S}}_i\dot{q}_i \quad \cdots\cdots (2)$$
$$\mathbf{f}_i^B = \mathbf{I}_i\mathbf{a}_i + \mathbf{v}_i \times^* \mathbf{I}_i\mathbf{v}_i \quad \cdots\cdots (3)$$
$$\mathbf{f}_i = \mathbf{f}_i^B - \mathbf{f}_i^e + \mathbf{f}_{i-1} \quad \cdots\cdots (4)$$
$$\boldsymbol{\tau}_i = \mathbf{S}_i^T\mathbf{f}_i \quad \cdots\cdots (5)$$

$\mathbf{v}_i$: Velocity vector of body i (6 components)
$\mathbf{a}_i$: Acceleration vector of body i (6 components)
q_i : Generalized coordinate (joint values)
$\mathbf{S}_i$: Velocity transformation matrix
$\mathbf{I}_i$: Mass and mass moment of inertia of body i
$\mathbf{f}_i^B$: Resultant force exerted on body i
$\mathbf{f}_i^e$: External force exerted on body i
$\mathbf{f}_i$: Force exerted on the joint i which is on body i
$\boldsymbol{\tau}_i$: Force generated by joint i

Figure 4: Recursive formulation for the derivation of equations of motion.

A recently developed recursive algorithm for formulating and solving equations of motion is presented in this section. The equations of motion used in recursive formulation are shown in Fig. 4 (Haug, 1992, Featherstone, 2008). Once the velocities and accelerations of the generalized coordinates are determined, the velocities and acceleration of each body can be computed. Further, recursive formulation can be utilized to find the forces and moments acting on each link in a recursive fashion, starting from the force and moment applied to the rigid body, which is connected to the end of the multibody system (Sciavicco et al., 2000).

Although the equations are derived, the operations required for implementation are substantially difficult. Compared to the two other formulations, however, augmented formulation is easier in terms of operations because it uses absolute coordinates.

As the embedding and recursive formulations use relative coordinates, however, these formulations need additional computation to calculate the constraint force. Unlike augmented formulation, moreover, the values that are associated with relative motion between the bodies are explicitly calculated using the embedding and recursive formulations.

In the case of augmented formulation, the number of equations of motion is 6n+p, which is proportional to the number of bodies. As the computational time for the calculation of the inverse matrix is proportional to $(6n+p)^3$, the complexity of computation is $O(n^3)$ for solving the equations of motion.

The number of equations of motion derived using embedding formulation is 6n-p. As the computation time for the calculation of the inverse matrix is proportional to $(6n-p)^3$, the complexity of computation is $O(n^3)$ for solving the equations of motion for the multibody system. As the matrix of embedding formulation is smaller than that of augmented formulation, the computational efficiency of embedding formulation is better than that of augmented formulation.

Unlike the two other formulations, recursive formulation does not need to assemble a system of equations of motion for each body as it is a recursive method. Therefore, although the number of matrices increases in proportion to the number of bodies *n*, the size of the matrix of the equations of motion is always 6×6. Consequently, the complexity of computation is O(n) for solving the equations of motion (Stejskal et al., 1996). In this study, due to the computational efficiency, recursive formulation was used to derive the equations of motion.

3.2 External Forces for the Dynamic Response Analysis

Eq. 1 shows the external forces considered for the dynamic response analysis. The external forces consist of the hydrostatic forces with nonlinear effects considering wave elevation, the linearized hydrodynamic force, the mooring force, the aerodynamic force, and the gravitational force, as follows:

$$\mathbf{f}^{e}(\mathbf{q},\dot{\mathbf{q}},\ddot{\mathbf{q}},t)=\mathbf{f}_{Hydrostatic}(\mathbf{q},t)+\mathbf{f}_{Hydrodynamic}(\dot{\mathbf{q}},\ddot{\mathbf{q}},t)+\mathbf{f}_{Mooring}(\mathbf{q}) +\mathbf{f}_{Aerodynamic}(\mathbf{q})+\mathbf{f}_{Gravity} \quad (1)$$

The module for calculating the external forces is developed, and it is used for the dynamics kernel (Ku et al., 2011).

4 MULTIBODY DYNAMICS KERNEL IN DISCRETE EVENT SIMULATION

In the previous section, the development of the dynamics kernel was presented. However, it is hard to deal with the discontinuous state variables, event triggered conditions, and state triggered conditions using the dynamics kernel. To overcome this limitation, this study adopts the DEVS (Discrete Event System Specification) formalism to develop the simulation program.

4.1 DEVS (Discrete Event System Specification) Formalism

The DEVS formalism, a set-theoretic formalism, specifies '*discrete event systems*' in a hierarchical and modular form. The DEVS formalism consists of two kinds of models: an atomic model and a coupled model. The atomic model is the basic model and has specifications for the dynamics of the model. Formally, 7 components, which are state variables, input events, output events, external transition function, internal transition function, output function, and time advance function, specify the atomic model. The coupled model provides the method of assembly of several atomic and/or coupled models to build complex systems hierarchy. Each DEVS model, either atomic or coupled, has correspondence to an object in the real-world system to be modeled (Zeigler, 1990, Zeigler et al., 2000).

However, the simulation progresses by changing the state variables for not only every event but also every unit time. Thus, the DTSS (*Discrete Time System Specification*) model is combined with DEVS model. The atomic model of DTSS is composed of 7 components, which are state variables, input events, output events, external transition function, output function, integral function, and state event function. The simulation model is called 'combined DEVS and DTSS simulation model'. In this paper, for simplicity, the simulation model will be called 'DEVS simulation model'.

In this study, each facility shown in Fig. 1 is modeled as an atomic model based on DEVS formalism, and the coupled models are defined by assembly of the several atomic models. In the next sub-section, it will be explained how to define the atomic model and the coupled model for the simulation of the process planning in shipbuilding.

4.2 Modelling for the Simulation of the Process Planning in Shipbuilding

A ship is a huge structure made up of a large number of hull structural parts called block. For example, A deadweight 300,000 ton VLCC (Very Large Crude oil Carrier, hereafter simply referred to as the '300K VLCC'), which has a length, breadth, and depth of about 320 m, 60 m, and 30 m, respectively, is divided into a number of building blocks (e.g. about 200 building blocks in the case of the 300K VLCC) as shown in Fig. 5.

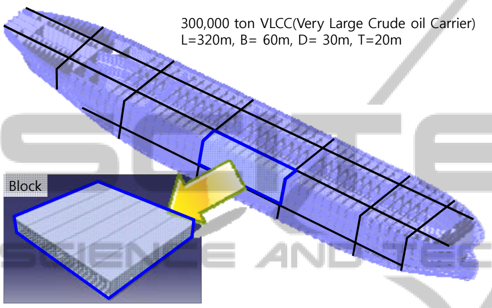

Figure 5: Very large crude oil carrier and its block.

Each block is assembled in an assembly shop near the dock, and the blocks are waiting on the PE (Pre-Erection) area. Then, the blocks are moved into the dock by using a goliath crane and welded together according to a suitable sequence, called the block erection, as shown in Fig. 6. Basically, the construction process of a ship is similar to that of a large product by use of Lego blocks.

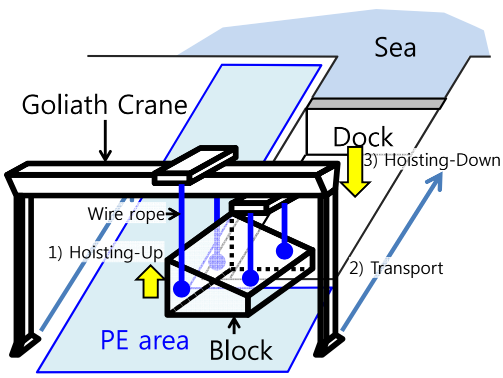

Figure 6: Block-lifting and transport process.

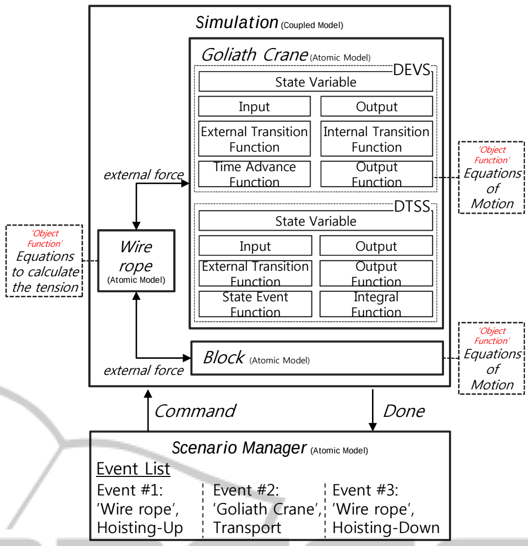

Figure 7: DEVS simulation model for the block-lifting and transport simulation.

Fig. 7 shows how to define the atomic model and the coupled model for the simulation of the block-lifting and transport process. The goliath crane, the wire rope, and the block are defined as atomic models. The each atomic model is connected with the object function. Each object function has the mathematical model of the atomic model. For instance, the object functions of the goliath crane and the block have their equations of motion, and the object function of the wire rope has the equation to calculate the tension considering its physical properties, such as wire length and elongation. The *dynamics kernel* is used as the *object function* for the dynamic analysis. The atomic models of the facilities exchange the external forces each other.

Beside these three models, also the scenario manager, which manages discontinuous events, is defined as an atomic model. We can see the event list, composed of hoisting-up, transport, and hoisting-down are defined for the block-lifting and transport simulation. Every event contains the name of the atomic model and the behavior. For example, event #1 means that the atomic model 'wire rope' will carry out the event 'hoisting-up'.

Fig. 8 shows that how the events are dealt by sending messages between the atomic models. To trigger event #1, the scenario manager sends the massage 'hoisting-up' to the model 'wire rope' and waits until the event is done by the model 'wire rope' (Fig. 8-a). After receiving the massage 'done' from the model 'wire rope', event #2 will be triggered with same sequence with event #1 (Fig. 8-b).

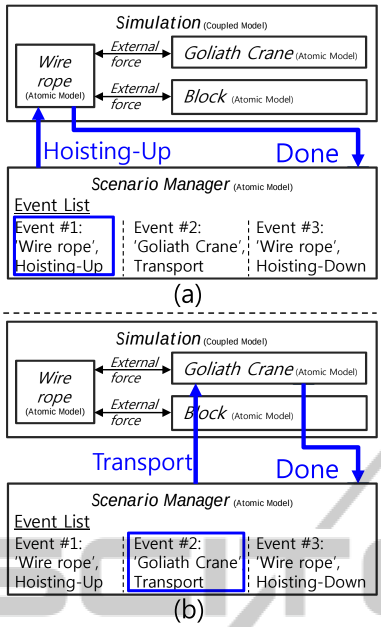

Figure 8: Sequence of sending messages between the atomic models.

After modelling the goliath crane, wire rope, and block using DEVS simulation model, shipbuilding process, which is composed of several discontinuous stages, can be easily simulated by defining the event list.

5 APPLICATION TO SIMULATION OF BLOCK- LIFTING AND TRANSPORT

This section presents an example of block-lifting and transport and the result of the simulation.

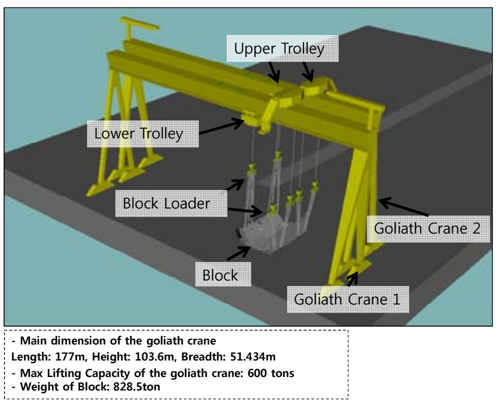

Figure 9: The goliath cranes and block model in the simulation of the block-lifting and transport.

The block-lifting and transport is carried out using two goliath cranes, six block loaders, and one block models. The goliath crane is composed of a main body, upper trolley, and lower trolley. The upper trolley and lower trolley are interconnected by sliding joints with main body. The block loader consists of two bodies, interconnected by revolute joints with each other. As explained in sub-section 3.1.2, the equations of motion, i.e. the dynamics model, are generated by using recursive formulation. Fig. 9 shows the goliath cranes and block model in the simulation of the block-lifting and transport.

Discrete events of the simulation are as following;

a. Hoisting-up the block

b. Transportation of the block by moving the goliath crane to the dock

c. Block turn-over: the process of turning the block upside down.

d. Hoisting-down the block

Fig. 10 shows the simulation results. The graph shows that tension of the wire rope, which is marked with red.

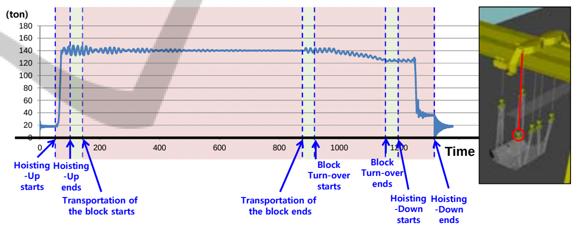

Figure 10: Tension of the wire rope, which is marked with red, calculated by using developed program.

The weight of the block is about 830ton. Therefore, around 140ton is reasonable amount of the tension, because there are total six wire ropes. We can also see that dynamic responses are different according to the events such as hoisting-up, transportation, turn-over, and hoisting-down, which means that the developed program can deal with the discrete events.

6 CONCLUSIONS AND FUTURE WORKS

A simulation framework was proposed and implemented in this study. The dynamics kernel is integrated into the discrete event simulation program for the process planning in shipbuilding. To evaluate the efficiency of the implemented simulation program, it is applied to the simulation of the block-lifting and transport.

As future works, we will apply the developed program to various simulation systems for process planning in shipbuilding such as the simulation of dynamic analysis of offshore structures and block assembly processes in order to improve the efficiency and applicability of the proposed simulation program.

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