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Integrated wheel loader simulation model for improving performance and energy flow

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A B S T R A C T

This paper describes an integrated wheel loader simulation model for improving performance and energy flow. The proposed integrated wheel loader simulation model includes a driver model that is designed to perform the two objectives of working and driving. The driver model for working was designed according to eight conditions considered as events and environment information. The driver model for driving is composed of throttle, brake, and steering inputs which represent an actual driver's input characteristics. By analyzing experimental test data of V-pattern working, human driving characteristics have been derived and applied in the driver model by using linear quadratic regulator (LQR) and model predictive control (MPC). The wheel loader dynamic simulation model with the driver model used in this study consists of four parts: mechanical powertrain, hydraulic powertrain, vehicle dynamic model, and working dynamic model with a simplified load model. All simulation models have been constructed in the Matlab/Simulink environment, and the proposed driver model has been validated from experimental test data. Working performance with the optimized path, energy flow, and loss analysis during V-pattern working was predicted and evaluated with the developed human driver and dynamic simulation model of a wheel loader. The driver model can be utilized in the design stage for prediction and evaluation of a wheel loader's working performance. It is also expected that an investigation of the optimal working pattern and energy flow for various working cycles of wheel loaders will be possible with the driver-model-in-the-loop simulation.

1. Introduction

Wheel loaders constitute one of the most important heavy vehicles in construction sites since they can exhibit high performance for transporting materials. Since a wheel loader is exposed to rough environments and delivers heavy materials, it is important to consider the prediction and evaluation of working performance and energy efficiency. Accordingly, it is necessary to predict and evaluate working performance and energy efficiency through a prototype; however, a physical prototype of a wheel loader is very expensive and consumes an enormous amount of time. Therefore, a virtual prototype that can represent the actual dynamics of a wheel loader is required to minimize the consumption of time and expense of making a prototype.

Several previous studies have developed a wheel loader's dynamic simulation model and driver model. Fales et al. [1] presented dynamic modeling, controller design, and virtual reality (VR)-based human-in-the-loop real-time simulation for a wheel loader control system. A true dynamic model of the machine includes several components, such as the engine, engine controls, digging forces, tires, drive train, traction, etc. However, the dynamic system was assumed to have limited wheel loader electro-hydraulics and linkage, since the linearized hydraulic and linkage model were used for real-time simulation and control based on virtual reality (VR). Cobo et al. [2] studied an electro-hydraulic open centered non-pressure compensated valve control system to evaluate the potential gains of implementing digital velocity servo control. The control objectives are to meet operator perceived response and smoothness requirements, and create a sub-system that could accept commands from an autonomous high-level planning controller. Haggag et al. [3] presented a new steer-by-wire (SBW) system which we designed, modeled, analyzed, and tested on wheel type loader construction equipment. Filla et al. [4] presented the initial results of a simulation model of a human operator. Rather than allowing the operator model to follow a pre-defined path with control inputs at given points, it follows a collection of general rules that together describe the machine's working cycle in a generic way. Keincke et al. [5] proposed the human perception process by discrete event techniques that also enable human deficiencies to be addressed. The objectives of previous researches were to analyze the working and dynamic behavior of the wheel loader through utilizing a dynamic simulation and operator model.

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In this study, a driver model for the wheel loader V-cycle working pattern and a 3D dynamic simulation model have been developed to analyze working performance and energy flow in each component of the wheel loader. In addition, a driver-model-in-the-loop simulation has been conducted using the developed driver model. V-cycle working experimental data have been analyzed to develop a driver model and derive a driver's working pattern. The proposed driver model consists of a working and driving module to express the full working cycle, called V-pattern working. V-pattern working constitutes typical working divided into four stages. The wheel loader fills up the bucket with materials at the first stage and goes back to the proper point to go to the unloading point at the second stage. At the third stage, the wheel loader approaches the unloading point to unload the material, and returns to the initial point after unloading the material at the fourth stage. The wheel loader that is the subject of this study and typical V-pattern working are shown in Fig. 1.

The driver intends to generate working and driving inputs sequentially according to the perception of working and driving states, such as cylinder displacement and wheel loader velocity, that are considered as events. To generate and represent human inputs, such as throttle, brake and steering behavior, some vehicle driving experimental data and V-pattern working experimental data were analyzed. Eight events can be defined in V-pattern working by experimental data for the driver model. The linear quadratic regulator (LQR) control algorithm has been used for generating driver's brake input, and the steering input has been determined by the model predictive control (MPC) algorithm, so that the wheel loader can track the path that is expected by the driver. The MPC algorithm is a well-known controller that can represent human steering characteristics. The developed and validated wheel loader dynamic simulation and driver model were used to predict and evaluate the performance of the wheel loader with regards to working time and energy consumption by changing the expected path of V-pattern working. Experimental V-pattern working and simulation results demonstrate that the dynamic simulation model with the virtual driver model can represent the wheel loader's actual dynamics and driver's behavior. By utilizing the developed wheel loader virtual simulation model and driver model, evaluation of performance and energy flow analysis has been performed based on V-pattern working by applying some expected paths.

2. Configuration of the integrated wheel loader simulation model

Fig. 2 presents the configuration of the proposed integrated wheel loader simulation model, which consists primarily of the driver model, driving powertrain model, hydraulic powertrain model, 3D multi-body dynamic model, working part dynamic model, and load model. The driver model generates throttle, brake, and steering inputs by environment information, and vehicle and working states, which refer to the position of the material and truck, vehicle speed, cylinder displacement, etc. Drive and hydraulic powertrain transmits power from the engine to the vehicle wheel and cylinder for driving and working. Since the transmitting process involves a loss of energy by a non-conservative force, such as a friction force, and results in low energy efficiency, analysis of energy loss and efficiency has been conducted by using the proposed simulation model.

Many researches about load models have been conducted to represent actual wheel loader dynamics with driver models [2,6–8]. The proposed load model in this paper consists of driving load and working load, driving load of rolling resistance, and air resistance, which are calculated by vehicle states, which are velocity, wheel speed, and vehicle weight. The working load model is a simplified model that can calculate horizontal and vertical resistances by material density, material slope, and some coefficients. Working load consists of the horizon and vertical material load at the bucket, and the load can be determined by bucket position and velocity with consideration of material weight. In addition, the proposed load models were validated by comparing experimental data with simulation results of the V-pattern working cycle. All of the sub-models, including the engine, torque converter, transmission, shaft between the wheel and transmission, pump, valve, and cylinder in the powertrain have been modeled mathematically based on actual dynamics and experimental map data in the Matlab/Simulink environment [9,10].

2.1. Powertrain model

The powertrain model of the wheel loader consists of the mechanical powertrain and hydraulic powertrain, which comprise the torque converter (T/C), automatic transmission (A/T), pumps, valves, and cylinders. The engine is the power source of the loader, and the transmitted power from the engine is divided into the drive and hydraulic powertrain by the torque converter and pump. The torque converter is coupled to the pump that is connected to the hydraulic system, and the pump torque of T/C is considered as a load applied to the engine. The shaft connected to the front wheel and rear wheel is connected directly to the transmission, so that the wheel loader is able to demonstrate good performance in working. Finally, shaft torque from the transmission is transmitted to each wheel by the reduction gear and differential gear. Modeling of the final reduction and differential gear has not been performed in this paper since the objective of this study is focused on the evaluation of performance and overall energy flow without the transient response of gears. Fig. 3 describes the configuration of the powertrain system of the wheel loader.

One part of the engine power is transmitted to the wheel through the mechanical powertrain for driving, and the remaining part of the engine power is transmitted to cylinders for working and steering. The pump is connected to the engine with a torque converter directly in order to transmit power from the engine to the hydraulic system.

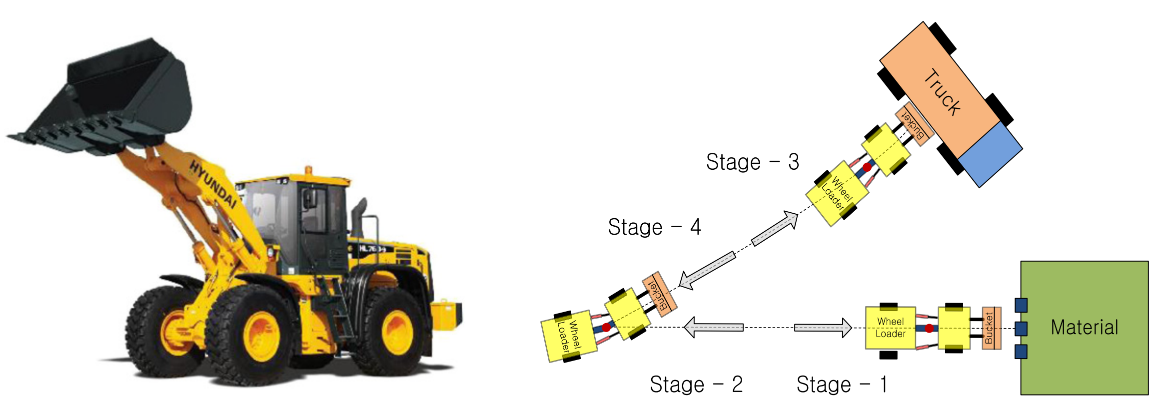

Fig. 1. Wheel loader and V-pattern working cycle.