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Journal of Terramechanics 69 (2017) 23–32

Journal of Terramechanics

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Effectiveness evaluation of hydro-pneumatic and semi-active cab suspension for the improvement of ride comfort of agricultural tractors

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Received 9 March 2016; received in revised form 10 September 2016; accepted 29 October 2016

Available online 11 November 2016

Abstract

Advances have been made to agricultural tractors to improve their ride comfort. However, the ride comfort of tractors is relatively low compared to that of passenger vehicles. Many researchers have developed various types of suspension for tractors. While most studies have focused on the geometry of the suspension, few studies have been carried out on the development of a control algorithm for tractor suspension.

In this paper, to improve the ride comfort of an agricultural tractor, a hydro-pneumatic suspension model with a semi-active suspension control is developed with computer simulation, and the effectiveness of the suspension is evaluated before the vehicle is equipped with the suspension and placed into production.

An optimal control algorithm for the semi-active suspension of the tractor is developed using a linear quadratic Gaussian. In the simulation, a hydro-pneumatic suspension system model is developed using SimulationX and is applied to a full vehicle model using MATLAB/Simulink. The suspension is assessed by experiments and simulations. The ride comfort using the ride comfort index according to ISO 2631 is evaluated by comparing a vehicle with a passive cab suspension to that with a hydro-pneumatic suspension applied with the semi-active control.

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Keywords: Agricultural tractor; Hydro-pneumatic suspension; Semi-active cab suspension; Ride comfort; Evaluation

1. Introduction

Operators of agricultural tractors are subjected to undesirable vibration which occurs when the tractor is operating. The vibration is continuously transmitted to the human body through the vehicle and long exposure to the vibration can cause adverse health effects (Prasad et al., 1995; Park et al., 2013; Cvetanovic and Zlatkovic, 2013; Cutini et al., 2016; Scarlett et al., 2007). The ISO 2631-1 (2004) provides an evaluation of human exposure to whole body vibration (WBV). The Society of Automotive Engineers (SAE) J1013 (2007) also suggests measurements of WBV for seated operators of off-highway work machines, which was superseded by ISO 2631. In addition, ISO 5007 (2003) suggests a laboratory method for measuring and evaluating the effectiveness of seat suspension on agricultural wheeled tractors. ISO 5008 (2002) defines the measurement procedures of the WBV of the operator from agricultural wheeled tractors and field machinery,

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http://dx.doi.org/10.1016/j.jterra.2016.10.003

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including operating conditions of the machine and the artificial test tracks.

An agricultural tractor has unique characteristics which make it substantially different from many other vehicles, especially passenger cars. The geometry of the vehicle means that the operator is seated in a high position. Relatively small pitch motions of the vehicle thus produce large motions of the operator of the tractor (Crosby and Allen, 1974). The different features of the tyres, such as their stiffness and damping coefficients, depend on the vehicle forward speed (Lines and Murphy, 1991; Crolla et al., 1990). Numerous researchers have modeled agricultural tractors in order to understand their vibration (Prasad et al., 1995; Ahmed and Goupillon, 1997; Tewari and Prasad, 1999). The tractor vibration has been predicted and various suspensions have been developed for tractors to improve ride comfort. Three suspension approaches have been developed for tractors: (1) seat suspension; (2) cab (cabin) suspension; and (3) axle suspension.

While the seat suspension positively affects the operator, it is difficult to achieve comfort for the operator. The suspension function depends on the change of the weight on the seat suspension according to the operator's weight, which affects the deflection and natural frequency of the seat suspension (Suggs and Huang, 1969). When the vehicle operating speed increases, it is not possible to ensure that the seat suspension meets the WBV guidelines for human health (Claar, 1983). Therefore, alternatives to seat suspension are used, such as cab suspension and axle suspension, even though they are difficult and expensive to apply to an agricultural tractor (Prasad et al., 1995; Achen et al., 2008). Specifically, cab suspension effectively enables the cab to isolate from the high frequency vibration of the engine, steering wheel and other components. With cab suspension, the changes in operator weight are less important because the total operation system of the cab suspension is dominated by the relatively greater weight of the cab (Suggs and Huang, 1969).

For several years, cab suspension has been developed to reduce the effect of the vibration of the tractor. Earlier studies on cab suspension focused on the structures and components of suspension (Suggs and Huang, 1969; Hilton and Moran, 1975), while later studies focused on the optimization of passive cab suspension (Rakheja and Sankar, 1984; Hansson, 1995; Mehdizadeh, 2015). In passenger cars, semi-active suspension and active suspension are general technologies used in the automotive control engineering. However, until recently, semi-active cab suspension with its developed control algorithm had not been applied to agricultural tractors. While the air ride system and the magnetorheological (MR) system have been developed for smooth operator ride (Achen et al., 2008; Brown, 2011), few studies have specifically been conducted on the actuators of a suspension model.

This paper focuses on the hydro-pneumatic and semi-active types of cab suspension. The effectiveness of the hydro-pneumatic and semi-active cab suspension is evaluated for the improvement of ride comfort in an agricultural tractor. Previously, we compared the passive and semi-active cab suspension of a tractor and showed that the tractor vibrations were effectively reduced by applying semi-active cab suspension using the linear quadratic regulator (LQR) method (Sim et al., 2014). Semi-active suspension control methods can be widely applied in on-road vehicles such as cars, trucks, and motorcycles (Spelta et al., 2011; Savaresi and Spelta, 2009). The factors of comfort and ride-holding have a trade-off relationship, and optimal control theories are used for the optimal performance of the system (Poussot-Vassal et al., 2012; Savaresi et al., 2010). In this current study, we convert the LQR control into linear quadratic Gaussian (LQG) for an estimator of vehicle states and apply the control to a full vehicle model of the tractor. A hydro-pneumatic suspension model is developed and applied to a 14 degree-of-freedom full tractor model. The effectiveness of the suspension is evaluated by the level of ride comfort according to ISO 2631.

The process of the evaluation of ride comfort for the system is shown in Fig. 1. The paper is organized as follows. In Section 2, indices of ride comfort and those of validation for simulation are introduced. Section 3 describes the controller of a semi-active suspension for a tractor using a quarter-car model and optimal control theories. Section 4 discusses the development of the simulation model of the hydro-pneumatic suspension using SimulationX and the model is verified with the hardware test data. In Section 5, the improvement of ride comfort through simulation is evaluated, demonstrating that the agricultural tractor with a hydro-pneumatic and semi-active cab suspension is superior to that with the rubber mount. Finally, Section 6 provides a conclusion to the paper.

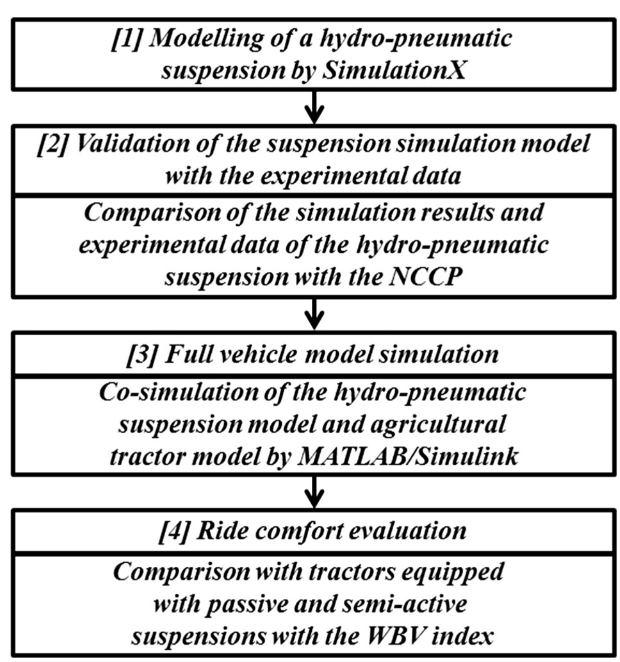

Fig. 1. Process of evaluation of ride comfort for tractor system.

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