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A virtual yaw rate sensor for articulated vehicles featuring novel electro-hydraulic steer-by-wire technology

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ABSTRACT

Steer-by-wire technologies remain under rigorous research and development given the advantages that they offer over their traditional counterparts. The spectrum of steering systems encompasses applications in the automotive, construction, agricultural, and aerospace industries, to name a few.

An original electro-hydraulic steer-by-wire technology based on pump displacement control actuation, an energy efficient alternative to conventional valve control, has been previously proposed by the authors. The new concept was validated and implemented on an articulated steering prototype test vehicle, and resulted in significant fuel savings and machine efficiency increase. This paper investigates the notion of virtual sensing relative to estimating the vehicle's yaw rate by only measuring the articulation angle and vehicle speed. Virtual sensing is a promising concept for yaw stability control and is an attractive option for vehicle manufactures as it reduces sensor cost, maintenance, and machine downtime. The designed yaw rate sensor is validated in simulation as well as on a test vehicle by devising appropriate steering maneuvers.

1. Introduction

Power steering systems have been employed for over a century to assist vehicle operators in overcoming the resistance experienced at the steering wheel. While this meek function was acceptable in the past, modern requirements are far more stringent. Power steering systems are expected to be smarter, smaller, lighter, and more efficient. Researchers have been making strides towards meeting the above objectives with the introduction of more complex hydraulic control valves, electric and electro-hydraulic power steering systems, to name a few. However, for larger vehicle applications with high power generation, efficiency remains a major concern especially with the skyrocketing fuel prices.

One sector that is striving to improve fuel efficiency is the mobile machinery industry, which heavily relies on hydraulic valves for motion control. While hydraulic valves offer adequate performance, they suffer from poor energy efficiency due to flow throttling losses across their ports. An alternative to conventional valve control is pump displacement control whereby the flow rate to the actuator(s) is varied by controlling the prime mover speed, the pump displacement, or both. Previous research involving the use of a particular variant of pump displacement control actuation, dubbed in literature as Displacement Control (DC), for realizing motion control in mobile machines has shown significant fuel savings in wheel loaders (Rahmfeld & Ivantysynova, 2004) resulting in 15% fuel savings, skid steer loaders (Williamson & Ivantysynova, 2007) resulting in 20% fuel savings, and excavators (Zimmerman, 2008) resulting in 40% fuel savings.

Nonetheless, DC has never been investigated for realizing the power steering function. A DC steering system is an electro-hydraulic steer-by-wire solution that promises fuel efficiency, variable-rate and variable-effort steering, yaw stability control via active steering, improved operator feel, and enhanced machine performance. Previous work by the authors (Daher & Ivantysynova, 2013b) investigated and validated the fuel savings, productivity, and efficiency of the new DC steering system. This paper deals with the derivation of a virtual sensor to estimate the yaw rate, which is a necessary state for realizing yaw stability control via active steering.

From a vehicle dynamics standpoint, articulated vehicles have been the subject of previous research given the type and severity of lateral instabilities that can occur in such vehicles, which emphasizes the relevance of the work in this paper. In Scholl and Klein (1971), the authors studied the steering system's effect on the stability of articulated vehicles, in which they concluded that the oil mass resonance was the most critical parameter

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affecting the system's closed loop stability. The work presented in Crolla and Horton (1983) details the derivation of a theoretical 3-DOF dynamics model that describes the handling behavior of articulated vehicles both on- and off-road in order to investigate stability at higher speeds. The model is linearized and the steering actuators are modeled as an equivalent torsional spring and damper at the articulation joint. The researchers Horton and Crolla (1986) later included a model of the steering system based on linearized pressure build-up equations to allow for stability analysis while incorporating the steering system effects. Simulation results revealed the impact that the steering system characteristics have on the stability of articulated vehicles, and identified the leakage across the hydraulic cylinders as a critical design parameter to control stability with higher leakage leading to reduced snaking oscillations. Their findings also confirmed the fact that increasing the articulation joint friction results in reduced oscillations due to the increased structural damping effect that friction introduces. More than a decade later, Chen and Tomizuka (1997) proposed a control oriented dynamic modeling approach based on the Lagrange mechanics, mainly for tractor-semitrailer vehicles in an Automated Highway System with lateral control as their primary focus. The authors designed two control algorithms for lateral guidance: one was a baseline steering control algorithm and the second was a coordinated steering and independent braking control algorithm. A linearized dynamics model was presented in He, Khajepour, McPhee, and Wang (2005) in which the authors devised a linear model of the steering system using a rotary proportional valve instead of the linear valve, which was considered by Horton and Crolla. The research was carried on by Azad (2006) where the author investigated the lateral stability of articulated machines with a rear-mounted load interacting with the ground, such as forestry skidders, and investigated the impact of locking the front and rear differentials on stability. From an active safety standpoint, the author also investigated the concepts of engine torque vectoring and differential braking to help stabilize the otherwise unstable vehicle via the design of robust control algorithms. This paper establishes the foundations for implementing active safety via the new DC steer-by-wire system.

The remainder of this paper is organized as follows: Section 2 introduces the new DC steering system; Section 3 provides a dynamic model of the entire system consisting of the steering hydraulic subsystem coupled to the vehicle dynamics model, which is based on the authors previous work (Daher & Ivantysynova, 2013a, 2013c); Section 4 deals with the derived single-input single-output (SISO) linear time-invariant (LTI) system, which is used for designing two state observer variants for estimating the yaw angle rate; Section 5 includes the validation of the designed observer by comparison against measured data on a prototype test vehicle, followed by conclusions in Section 6.

2. Displacement Controlled steer-by-wire technology

Displacement Controlled (DC) steering is an electro-hydraulic steer-by-wire system that interprets the operator's input at the steering wheel and adjusts the displacement of a variable displacement pump to control the fluid flow rate to the steering actuator(s). Fig. 1 is provided for identification of components in the proposed circuitry. The actuator (8) motion is controlled by adjusting the pump (2) speed, displacement, or both. The pump input/output ports are connected to the piston/rod sides of the actuator. The differential fluid flow between the actuator's uneven sides is overcome by means of pilot-operated check valves (6), which keep the low pressure side of the actuator connected to a low pressure source that can either provide or absorb flow to prevent evacuation. The low pressure source has its own fixed displacement charge pump (4), driven by the same prime mover (1), providing continuous flow to the cylinder's low pressure side. The low pressure level setting is adjusted via a pressure relief valve (5). The system is protected from over-pressurization by means of pressure relief valves (7) installed on both sides of the actuator. The pump control system (3), sketched in Fig. 2, uses a single stage proportional control valve that meters flow to a double rod actuator mechanically coupled to the pump swash plate.

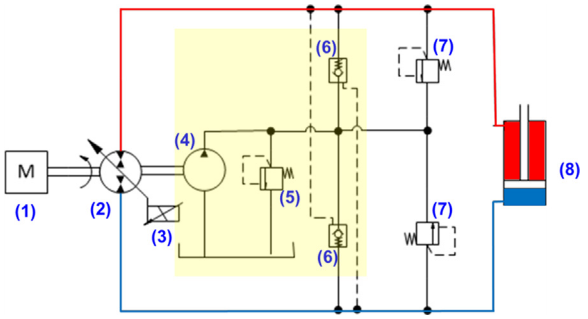

Fig. 1. DC steering hydraulic schematic.

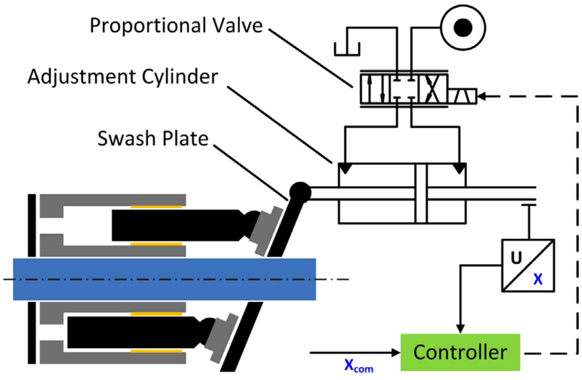

Fig. 2. Pump swash plate control system.

The actuator linear displacement determines the angular position of the swash plate, and therefore the effective instantaneous pump displacement volume per revolution.

3. System plant model

The plant model of the new DC steering system includes two submodels: hydraulics and mechanics. Fig. 3 shows a block diagram of the system model. The hydraulics module delivers the required flow rate to induce linear motion in the steering actuator, which translates into vehicle articulation. The pressure levels in the actuator sides are determined by the load levels computed within the mechanics module mainly due to the opposing loads generated at the ground–tire interface.

The reader is encouraged to read the authors previous work (Daher & Ivantysynova, 2012, 2013a, 2013b, 2013c) for a complete and thorough derivation of the nonlinear models and their respective linearized models.

3.1. Mechanics subsystem

The mechanics subsystem is primarily composed of a multi-DOF vehicle dynamics model, shown in Fig. 4, which is derived based on the Lagrangian principle given as follows:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right)-\frac{\partial L}{\partial q_i}+\frac{\partial D}{\partial \dot{q}_i}=Q_i \qquad (1)$$