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METHODS TO REDUCE ENERGY CONSUMPTION IN THE HYDRAULIC SYSTEM TOWARD THE NEXT GENERATION OF GREEN, HIGH-EFFICIENT AGRICULTURAL TRACTORS

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Extended Abstract

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Agricultural tractors make massive use of hydraulic control technology. Being fuel consumption a big concern for agricultural applications, tractors typically use the state-of-the-art technology, load-sensing (LS) architecture, to allow good controllability in systems with multiple actuators while promoting higher energy efficiency. Several variants of LS systems have been proposed over the years, and research on cost-effective methods to further increase their efficiency is of high interest for original equipment manufacturers (OEMs) and the fluid power community.

In this PhD work, a 400 hp CNHi CCH agricultural tractor was taken as the tractor reference. Several energy-efficient solutions were proposed and demonstrated for the reference agricultural tractor hydraulic system, aiming at reducing the fuel consumption and increasing the system efficiency, but without affecting the functionality of the hydraulic control system. More importantly, facing the more stringent regulations on the CO2 emission and the rising consciousness of a greener environment in society, both industry and academia have investigated the use of electricity as energy carrier and storage. This dissertation also carries out the study on the possibility of electrification of the reference machine, focusing on the auxiliary hydraulic supply to the planter.

To achieve such objective, the quantification of the energy loss within the hydraulic system represents an important step to drive the development of cost-effective solutions. For this purpose, a combined approach of simulation and experimental testing has been undertaken to characterize the power distribution in the high-pressure circuit. Within the high-pressure hydraulic system of the referenced agricultural tractor, a non- linear model of the hydraulic system was developed through lumped-parameter approach and embedded in Simcenter Amesim modeling environment, building in-house models for every component of the system. Modeling is divided into four main parts named after the LS pump, the hitch control valve, the steering priority valve and the remote valve in both the circuit supplied by two LS pump. For the LS pump, the modeling of pressure compensator and flow compensator allows reaching a good agreement between simulation results and experimental data for both steady-state and dynamic behavior.

Experimental tests on the reference machine were performed through a test plan purposely developed within this research, and tests included different loads, oil temperature and engine speed. These tests were aimed at measuring both input and output hydraulic power within the system, permitting a gross analysis of the power loss through the system. More importantly, the test permitted to validate the model, so that the model can be used for in-depth studies of the power flow throughout the hydraulic system.

Focusing on the sources of the power dissipation on such systems, especially after learning that the remote control valves are responsible for up to 25% of power loss in the system, two different more energy-efficient solutions have been proposed to be tested firstly on the model, then on the reference machine to reduce the fuel consumption of the machine. Taking advantage of the increasing reliability and more affordable cost of electro-hydraulic components in recent years, both solutions involve the use of electro-hydraulic components (electronic proportional pressure reducing valves) to achieve a control logic that reduces the pressure losses in the control valves according to the load and the flow request. The Variable Pump Margin (VPM) solution uses an electro-hydraulic pressure reduction valve as one possible way to lower the pump pressure margin, and it reduces the pressure drop across the local pressure compensator upstream of the main LS valve. The Hybrid Variable Margin (HVM) solution requires an additional electro-hydraulic pressure reduction valve near the main LS valve to further lower the pressure drop across the main spool and the local pressure compensator. After the introduction of the general working principles for the proposed solutions, the potentials in terms of power savings are analyzed. The original HVM solution has significant benefits over the VPM solution, which is similar to techniques recently introduced by other researchers. The two main advantages of the HVM solution consists of a higher energy-efficiency or the potential for sizing the system by using down-sized components to lower the required volume and cost of the system. The solutions are studied not only through simulations, considering a high-fidelity model for the reference circuit. But also the VPM solution has been tested out on the reference tractor. High oil temperature and high engine speed circumstances have been the focus of this comparison, where different loading conditions and flow requests are performed. Results illustrate great potential of the fuel saving and a great matching between empirical and simulation results was seen. On average, when the pump is operating without any saturations, VPM contributes 6.7% power savings while HVM triples this number, hitting 15.6% power saving compared to the conventional system with single-function involved. The technology has high potentials for future applications to a wide spectrum of mobile applications.

Moreover, the main purpose of an agricultural tractor would be supplying an implement to carry out the tasks related to soil and crops. Focusing on the current pressure saturation issue presented when the tractor is connected with a 16-row Early Riser agricultural planter, a novel pressure control method for the load sensing architecture tractor with implement connected, aiming at improving the system efficiency and reducing fuel consumptions, has been proposed. The proposed solution, Intelligent Pressure Saturation Control (IPSC), allows better integration of tractors and implements controls, effectively reduce the power loss introduced by the throttling oil through the second set of hydraulic valves, thus reducing the heating of the oil through the system without major physical changes on the circuit, which makes such solution stands out compared to other solutions such as independent metering. Additional reduction in parasitic losses is possible since the cooling fan is not required to run that fast to cool down the oil, which further enhances the advantage of the solution compared to the current system from an economic and environmental point of view. These all make the IPSC solution cost-effective and attractive to related industries. Simulation results, together with stationary and in-field tests showed that the IPSC solution can achieve up to 46% of mechanical power reduction at the pump shaft for two different crop types, leading to a 38% improvement in soybean system efficiency under most frequent working conditions and 34% in corn.

On top of the IPSC strategy, more intelligent control algorithm is explored by proposing a new system architecture to fully incorporate both of the LS pumps with all of the EHRs, to achieve dynamic regrouping control (DRC) or static regrouping control (SRC). The dynamic regrouping strategy provides more potential for the system to benefit from the IPSC solution by allowing both of the supply pumps to be able to supply to any functions that are activated in the circuit thus the system configuration changes in time under different operating conditions to minimize the power loss in the system. This strategy, when actively controlled, can lead to a further 32.6% power reduction compared to the IPSC solution, which results in a significant 46% power saving compared to the baseline condition. The results from the regrouping configuration can serve as a suggestive layout for the OEM when promoting such machines to the market.

Besides the hydraulic interface between the tractor and the implements, as well as following the trend of electrification in the area, different possibilities to electrify the planter circuit have been explored. Based on the successful example from the literature to supply electric power to the implement, a generator is mounted on the engine shaft to generate electricity, which is transitioned to the electric user end through inverters on the implement. Two different architectures of the electrified circuit are considered, namely Selective Purely Electrified architecture and Selective E-pump Architecture. Analytically, all feasible possibilities are gathered considering the efficiency and size of the electric machines. While the rest of the functions still are hydraulically supplied, the new engine shaft required for supplying both sections are summed up. It turns out that when replacing the alternator and the vacuum motors with the electric ones, have the cylinder system supplied by e-pump structure, the system could see possibility a 71.9% reduction in mechanical power supplied by the engine shaft. However, in this study, the cost of the newly added components has not been considered, which could potentially penalize the final choice of the system configuration when it comes to the decision of OEMs.

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Final remarks concerning benchmarks and strength points of the Pellizzi Prize 2024

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This PhD thesis encompasses both topics “Tractors and Engines” and “Agricultural Machines and Mechanization” of pertinence of the G. Pellizzi Prize.

The work proposed original solutions for increasing the energy efficiency of the high-pressure system of tractors and implements, in line with current societal needs for more sustainable agriculture. The approach followed numerical analysis, simulation, and different level of experimentation including full scale test involving a 400 hp tractor system. The work has proposed several new solutions (7), of different level of complexity and applicability. Energy savings up to 40% compared to the baseline commercial solution where measured, leading to a reduction of fuel consumption of about 7%.

The most remarkable impacts of the work are 7 peer-reviewed publications, including two prize papers, 4 awarded patents and 1 patent application. All publications were in journal of conference of primary importance in the field of agriculture and fluid power systems.