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Energy saving solutions for a hydraulic excavator

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Abstract

Nowadays the improvement of energy efficiency and the reduction of pollutant emissions are the major challenges that the mobile machinery manufacturers have to face with. With rising fuel prices and increasingly stringent regulations, the development of energy saving solutions and efficient hydraulic system have become a priority for researchers and OEM's. One of the most effective approach is the machine hybridization but other solutions can be adopted. This paper proposes with the aid of mathematical tools energy saving solutions for an excavator equipped with a load sensing hydraulic system. A comprehensive energy analysis was conducted through the excavator model to highlight the energy dissipations along the system. Different solutions to reduce losses and improve fuel saving including energy recovery from boom and arm and the introduction of a second pump in the flow generation unit were identified and investigated in detail. Finally, combining the proposed solutions, a new hydraulic hybrid excavator concept was obtained with a 15% of fuel saving.

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Keywords: Hydraulic Excavator; Load Sensing System; Energy Analysis; Fuel Saving.

1. Introduction

Over the last decades, energy saving and fuel consumption reduction are the most topical issues in the world of construction equipment as a logical consequence of more stringent regulations about pollutant emissions and the increasing fuel costs. In this context, the manufacturers of earth-moving machinery and OEMs have to meet market demands developing and offering new solutions with higher energy efficiencies.

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More efficient solutions concern the optimization of the power transmission [1] and of the matching between hydraulic system and internal combustion engine [2], analysis about energy dissipations through the hydraulic system [3], optimization of the engine auxiliary components [4] and of the valves performance [5], better control strategies and recuperation of potential and kinetic energies. In literature, new energy saving architectures have been proposed to reduce throttle losses and improve the system overall efficiency. Finzel et al. [6] developed an electro-hydraulic LS dual pump system dividing the users with similar loads and reducing the energy losses in the sections with lower loads during parallel operations; this solution shows an energy consumption reduced up to 30%. Kim et al. [7] presents an independent swing system installed on a 48 t excavator; by adopting a dedicated pump for the swing motor the pump power was reduced up to 12% compared to the standard one. An interesting solution is to separate meter-in and meter-out in hydraulic valves; this ensures better dynamic performance, increased functionality and the possibility to operate in more efficient ways. Hansen et al. [8] tested an independent metering valve system finding similar performances with traditional LS and a reduction of energy consumption of about 30%. Another architecture is the Displacement Control (DC) system in which each actuator is powered through a dedicated variable displacement pump or through a hydraulic transformer. This system permits to eliminate the lamination losses due to the contemporary actuation of more than one user, typical in valve-controlled systems. The good functioning of DC solution is proved by both numerical results and experimental tests carried out on prototype with fuel savings up to 40% [9]. One of the most effective approach to obtain energy saving and fuel consumption reduction in hydraulic excavators is the system hybridization and the application of energy recovery system. In particular, hydraulic hybrid technology reached a level of advanced development so that for several years the major excavator companies have been developing hybrid excavators prototype or have already made them available on the market [10-12]. Furthermore, new hybrid solutions have been proposed by the academia. Zhao et al. [13] developed an energy recovery system (ERS) exploiting three chamber cylinders and accumulators to recover the potential energy of mechanical arms and load of an excavator. The dissipated energy of the engine can be reduced by around 50%. Kim et al. [14] designed a new regeneration scheme to recover boom potential energy by directly connecting the head chambers of the boom cylinders to a variable displacement hydraulic motor installed on the engine shaft. Simulation results show fuel saving of 10% for the levelling cycle. Li et al. [15] proposed a novel layout for a 21 t excavator which exploits hydraulic accumulators to recover boom potential energy, kinetic swing motor energy and the overflow of the main relief valve, obtaining a 16% fuel saving and higher efficiency compared with the conventional machine. Vukovic et al. [16] developed a new constant pressure system for mobile machines, designed to ensure the engine working in high efficiency regions.

The aim of this paper is that of proposing energy saving solutions for Load Sensing (LS) hydraulic systems to improve the machinery efficiency and permits a reduction in fuel consumption. Starting from the energy analysis of the excavator, through its validated mathematical model, the distribution of the energy losses within the system have been investigated. Different solutions were identified to reduce losses and recover energy; each solution was analyzed in detail with a dedicated energy analysis to highlight pros and cons. At last, a new hydraulic hybrid excavator concept has been presented combining all energy saving solutions. Simulation results showed a 15% of fuel saving and a significant reduction in energy losses.

2. Mathematical model

A mathematical model of the machine was developed to accurately evaluate the energy distribution along the system. The investigated mobile machinery is a middle size (9 t) excavator whose hydraulic system is of a LS type. The excavator is equipped with a 46 kW Diesel engine and the hydraulic system is composed of a flow generation unit (FGU) comprising a variable displacement axial piston pump and an external gear pump, a LS flow sharing valve block with nine actuators (only the principal, i.e. boom; arm; bucket; swing and travels were modelled). The model is composed of hydraulic sub-models including a variable displacement axial piston pump, a load sensing flow sharing directional valve, a 2D kinematics model of the front excavation tool, turret and tracks and the engine model.

The pump mathematical model, presented and verified in [17-18], was conceived as a gray box model composed by the combination of white box model of the pump regulators, pressure and flow compensators, and the black box model of the pump flow characteristics for the accurate prediction of the swash plate motion. The mathematical model of the flow control valve block is a white box model, already developed and validated in [19-20] with a comparison between numerical and experimental results. The model is based on the following differential equations: