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Coupling excavator hydraulic system and internal combustion engine models for the real-time simulation

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ABSTRACT

Rising energy costs and emissions restrictions force manufacturers to exploit new techniques to reduce fuel consumption and pollutant production. Many solutions have been proposed for off-road vehicles, mainly based on reduction of hydraulic losses, better control strategies and introduction of hybrid architectures. In these applications the optimisation of the matching between hydraulic system and thermal engine is a major concern to improve system overall efficiency. The work presented in the paper is focused on the development of a method for the simulation of typical mobile machinery where hydraulic systems are powered by internal combustion engines; the proposed co-simulation approach can be useful in the development cycle of this machinery.

1. Introduction

Fuel consumption and pollutant emissions are and will continue to be the driving forces in the improvement of vehicles, i.e., cars, trucks as well as earth movers and construction machines. These aspects are amplified by more stringent emissions regulations that nowadays are going to impact also off-highway vehicles development. Many solutions have been proposed recently to reduce the energy consumption of off-road vehicles, mainly based on reduction of hydraulic losses, better control strategies of hydraulic systems and the introduction of hybrid architectures (Costlow, 2014; Inderelst, Losse, Sigro, & Murrenhoff, 2011; Altare, Padovani, & Nervegna, 2012). For off-road vehicles, the energy storage systems of an hybrid architectures could be electric batteries or hydraulic accumulators. If electric batteries have high energy density, hydraulic accumulators show higher power density and energy conversion efficiency that are needed to effectively recover mechanical energy (Erkkilä, Bauer, & Feld, 2013; Renz & Vogl, Brand; Conrad, 2008). A number of proposals can be found in the literature for the development of Hydraulic Hybrid Systems (HHS), as reported in (Conrad, 2008; Hui, Lifu, Junqing, & Yanling, 2011; Feng, Huang, & Li, 2011).

In the mentioned applications, the optimisation of the matching between hydraulic system and internal combustion engine is one of the major concerns for the improvement of system overall efficiency and the reduction of fuel consumption. Virtual design based on mathematical models is a widely used option to match system components making the best use of their operating characteristics. Generally speaking, this is the case when dealing with complex systems, where the ability to simulate interactions between system components in real operating conditions is a primary concern for the optimisation of system layout and management. When dealing with the simulation of hydraulic circuits and primary engines several problems arise, and this is probably the reason why up to now in most of the proposed models of hydraulic off-road vehicles thermal engine is not considered or otherwise is modelled following map-based approaches (several examples can be found in (Altare et al., 2012; Conrad, 2008; Hui et al., 2011; Feng et al., 2011; Ho & Ahn, 2012; Wu, Lin, Filipi, Peng, & Assanis, 2004; Filipi & Kim, 2010; Bender, Kaszynski, & Sawodny, 2013)), with very few and recent exceptions (Patil, Molla, & Schulze, 2012).

Mathematical models have been used within several steps of the design process in systems engineering, but with the continuing increase of computers power and the improvement of computational methods, simulation tools are currently used in every phase of the development cycle (the so-called V-cycle (Cosadia, Silvestri, Papadimitriou, Maroteaux, & Obernesser, 2013)). Usually, models with different levels of detail – and therefore with different complexity – are used at each stage of the development process. In the concept stage, very fast, low fidelity models are required for rapid architecture and concept analysis, while coming to an exhaustive design and optimisation of components and subsystems, detailed 1-D to 3-D models are used. Faster, lower fidelity

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Definitions

m	mass
n	rotational speed (in [r/min])
p	pressure
t	time
T	torque
V	volume
ρ	fluid density
η	efficiency

Subscripts

d	displacement
hm	hydro-mechanical
v	volumetric

Acronyms

F&E	Filling-and-Emptying
HHS	Hydraulic Hybrid System
ICE	Internal Combustion Engine
LS	Load-Sensing
MVM	Mean Value Model
QSF	Quasi Steady Flow
XiL	Model-in-the-Loop (MiL), Software-in-the-Loop (SiL), Hardware-in-the-Loop (HiL)

models are employed for the system integration phase, and for the development and testing of control systems (i.e., ECU, control strategies, etc.) through XiL (MiL, SiL and HiL) tools.

As a matter of fact, modelling tasks carried out throughout the development cycle involve very often the use of disparate simulation tools, each committed to a specific sub-system (e.g., AMESim® for the hydraulic system, GT-Power®, Boost® or Simulink® for the engine, in the case of an HHS or a hydraulic excavator). Even if a single simulation tool may be considered within all stages of the development process, actually this approach seems to require significant efforts in terms of costs and time.

The work presented in this paper is focused on the development of methods and techniques for mathematical simulation of typical mobile machinery where hydraulic systems are powered by internal combustion engines (ICEs).

By coupling models of a Diesel engine and the hydraulic circuit of an excavator by carefully handling causality, *I*/*O* parameters and co-simulation issues, a comprehensive mathematical model was set up and used to simulate steady and transient behaviour of the system. Different integration time steps were defined for the two sub-models taking account of their differing numerical "stiffness", thus allowing to run the comprehensive model faster than real time.

A potential of this approach is the ability to develop a comprehensive control strategy for the whole system, with the possibility to maximise performance and reduce fuel consumption in relation to the specific tasks for the system itself was developed; rather than considering the overall system as the sum of components, whose control strategies are optimised in reference to the execution of generic tasks, the general control strategy can be developed to maximise the performance of the individual components in the specific configuration adopted. The proposed models allow for the simulation of the whole system taking account of non-linear and dynamic behaviour of its components still running in Real-Time. Thanks to this, these models can be used within the design process both to define the system layout and to design and test related control strategies (since they can be embedded in XiL systems).

The engine model has been built in Simulink® following a "crank-angle" 0D, lumped-parameter approach and allows to take account of non-linearities and low-order dynamics typical of Diesel engines (Guzzella & Onder, 2010; Gambarotta, Lucchetti, & Vaja, 2011). The model of the hydraulic system was set up in AMESim® coupling the models of all involved components (axial piston pump, flow compensators, valves, actuators, etc.) to replicate the non-linear behaviour of the system with the typical fast dynamic. Kinematics of the system (e.g., arms, boom, bucket, etc.) were simulated using the proper AMESim® libraries (Casoli & Anthony, 2013; Casoli, Anthony, & Riccò, 2012). The developed models were coupled to co-simulate the behaviour of an excavator and the comprehensive model was validated comparing several calculated output with the first experimental data gathered on a real machine.

Results reported in the paper show to what extent the proposed co-simulation approach, based on dynamic model for both the hydraulic system and the internal combustion engine, could be useful in the control strategy development phase for hydraulic systems powered by Diesel engines.

2. Modelling of hydraulic system

The hydraulic system considered is based on a typical circuit of an excavator composed of a variable displacement axial piston pump with flow and pressure compensators, flow control valves and hydraulic actuators as described in (Casoli et al., 2012). Kinematics of the system (e.g., arms, boom, bucket, etc.) will be taken into account in the next future.

2.1. Variable displacement axial piston pump model

The pump considered in the paper is a variable displacement axial piston pump, Fig. 1. The comprehensive pump model includes three sub-models: the pressure compensator (PC), the flow compensator (FC) and the flow generator model.

2.1.1. Pressure and flow compensators models

The main purpose of the pressure compensator (PC) is to limit maximum value of system pressure (P line) when it is greater than a defined relief setting pressure. When this situation occurs the PC causes a rotation of the swash plate, reducing the flow rate and avoiding further increases of the system pressure. The task of the flow compensator (FC) is to offset pump displacement for a defined preload value by controlling the swash plate angle. As a common practice, a "load-sensing" pump is designed to keep a constant pressure drop across a controlling orifice in order to regulate fluid mass flow rate. In order to avoid wasting energy, the FC adjusts the pump displacement until the pump outlet pressure is greater than the load pressure of a defined quantity. The model used in this research was already presented in (Casoli & Anthony, 2013), in this work has been used a slightly simplified version of the original model where small redundant chambers and leakages, having limited effects on the pump dynamic behaviour, according to the Activity Index criteria (LMS Imagine, 2011; Louca, 2014). The corresponding volume increase of the remaining chambers had a positive effect to reduce numerical stiffness of the resulting model, according with Eq. (4) which clearly shows that hydraulic components have a considerably small time constant, due to the fact that