Automation in Construction 58 (2015) 144–154

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Systematic approach in the hybridization of a hydraulic skid loader

A. Bertini [b], M. Ceraolo [a], G. Lutzemberger [a,*]

[a] Department of Energy, Systems, Territory and Constructions Engineering, University of Pisa, Largo Lucio Lazzarino n. 1, 56123 Pisa, Italy
[b] IMER Group, Via Salceto n. 53-55, 53036 Poggibonsi, Siena, Italy

ARTICLE INFO

Article history:
Received 24 June 2014
Received in revised form 16 June 2015
Accepted 20 July 2015
Available online 5 August 2015

Keywords:
Skid loader
Working machine
Hydraulics
Power train modelling
Hybrid propulsion system
Lithium battery

ABSTRACT

In response to growing concerns on the environment and the need to save energy, working machine manufacturers have started to consider hybridization of their products. This paper presents a systematic modelling approach to identify the most promising hybrid configurations for existing skid loaders. This approach involves accurate modelling of the existing version (fitted with a conventional power train), model validation by matching the simulation results with experimental tests, design by modelling of different hybrid configurations and corresponding cost/benefit analysis.

1. Introduction

In response to growing concerns for environmental problems and the enhanced need to save energy, the demand for more environmentally friendly and fuel efficient working machines has rapidly increased in recent years [1]. In particular, during typical working operations, conventional skid loaders frequently stop and start, which generates significant amounts of braking energy that is normally converted into heat and thus loss in frictional or hydraulic braking systems [2]. Several energy-saving options can be considered to recover, store and reuse this energy. Much research has been carried out in this direction, as detailed in [3–5], which has also confirmed the validity of the usage of hybrid power trains in the field of construction machinery.

This paper reports on the design and development of different electric hybrid versions of an existing skid loader. The models were created using two different software packages, LMS Imagine.Lab AMESim [6] and 3DS Dymola [7]: both allow object-oriented modelling. The first one allows detailed and fully customizable component modelling using standard program languages, or even the import and use of Matlab-Simulink files; the other one is based on Modelica language [8], which allows the users to create their own models and comes with a great deal of totally open, well-tested models and libraries from all the fields of engineering (electric, magnetic, mechanic, thermal hydraulics, etc.).

To inspire readers with confidence in the quality of the models; first, the existing skid loader was modelled and validated by matching the simulation results and experimental tests. Later, new models were developed for different hybrid configurations, i.e. configurations in which electric power is combined with conventional (either hydraulic or mechanic or both) powers. The latter have been simulated on realistic duty cycles, defined in collaboration with the manufacturer.

2. The conventional skid loader

The conventional AS12 skid loader manufactured by Ihimer is shown in Fig. 1. Its main characteristics are summarized in Table 1. It is a small working machine normally employed to transport materials (i.e. soil or rubble) within construction sites. The conventional power train is composed of an ICE flanged to two independent pumps that, in turn, feed through hydraulic circuits two independent hydraulic motors driving the left and right parts of the vehicle. In fact, the skid loader is steered by differential speed of the two hydrostatic transmissions, and usage of independent pumps for each side is required. Another hydraulic circuit, in which a third pump is used, is aimed to feed the two linear actuators. A schematic representation of the hydraulic scheme of the skid loader is pictorially represented in Fig. 2. It shows that the ICE is flanged to three pumps. The two main pumps have variable displacement and are bidirectional, while the two hydraulic motors have fixed displacement. The other fixed gear pump supplies the linear hydraulic actuators, which moves the kinematic mechanism (in pairs), composed of the arm and the bucket. It must however be specified that the scheme of Fig. 2, in comparison to the real scheme, has been simplified, giving relevance to

Abbreviations: AUX, Auxiliary loads; BSFC, Brake-specific fuel consumption; ED, Electric drive; EG, Electricity generator; EM, Electric machine; EPC, Electronic power conditioner; ICE, Internal combustion engine; PC, Primary converter; PMM, Power management module; RESS, Rechargeable energy storage system; SOC, State of charge.

* Corresponding author: Tel.: +39 050 2217311.
E-mail address: lutzemberger@dsea.unipi.it (G. Lutzemberger).

http://dx.doi.org/10.1016/j.autcon.2015.07.013
0926-5805/

Fig. 1. Ihimer AS12 skid loader.

the main components and neglecting some other parts, i.e. details of the boost and of the oil conditioning section.

The hydraulic circuit used for propulsion contains some check and relief valves. The check valves are either wide open or completely shut, having a minimum or maximum hydraulic resistance, respectively. The other types of valves are modulating valves: they usually contain a closed loop analogue control system to control the fluid flow or pressure and to vary their resistance according to the flow rate or pressure differential [9]. These valves are normally used in pairs to maintain the pressure within a desired band, typically between 200 bar (i.e. the maximum allowed value for the hydraulic circuit under indication of the manufacturer for the considered machine) and 20 bar. The gear pump is used to supply both working hydraulics and boost section for the two hydrostatic transmissions in order to reduce the costs and the number of components.

On the other side, the hydraulic circuit feeding the actuators is based on the action of spool valves: the basic part is constituted by one or more metering orifices with variable cross-section areas able, through the spool action, to change the direction of the flow towards one or the other of the actuator chambers.

It must be specified that these last are proportional control valves, and they are able to perform pressure-flow rate metering according to the system architecture.

2.1. Modelling subsystems

The proposed models of the skid loader were built on both AMESim and Dymola. The results of simulation were comparable, which gives the authors confidence in the quality of the models. All subsystems have been modelled weighting accuracy and complexity for the purpose considered. Examples of hydrostatic simulation models can be found in [10–13], and also in reference to the power train machine architecture. Similar approaches in other fields are also followed in [14,15]. The main subsystems of these models are hereinafter analysed.

The internal combustion engine (ICE) model, the source for the vehicle energy propulsion, uses the characteristic torque and BSFC maps at partial and full load, and its mechanical inertia. The model includes the control of the fuel flow including over run fuel cut-off and idle speed control.

Hydraulic pumps and motors are modelled taking into account their inertia, and evaluating flow and mechanical losses through a map-based approach. Their efficiency is computed as a function of the shaft speed and the difference of pressure between input and output. The ideal flow rate is determined by the shaft speed, pump displacement and swash fraction; the latter, only in case of variable displacement pumps, while the real flow rate comes from the ideal one plus the addition of leakage, function of inlet pressure and difference of pressure between input and output.

As regards check and relief valves, it suffices to describe the static (algebraic) input–output relationship based on the input and output port pressures, since the speed of response of the valves is many times faster than that of the overall system [9]. Additionally, the hydraulic spool valves, i.e. the components that control the actuators' operation, have been accurately modelled: in this regard, a submodel of a 3 position 6-port hydraulic centre DC proportional valve has been defined and validated with experimental results. A simplified scheme of the valve is represented in Fig. 3.

The working machine kinematic model is defined considering the arm, bucket and joints dimension, mass and inertia, as a result of the CAD models provided by the manufacturer.

The vehicle dynamics is studied considering its longitudinal behaviour. Although, in the actual vehicle, the motors independently drive the left and right driving wheels (i.e. during turning, these motors have different rotational speeds due to different flow rates provided by the controlled pumps), in the models used for the study, the two motors are considered to be always rotating simultaneously and steering was not considered.

Vehicle resistance is evaluated by taking into account the usual term, composed of the rolling resistance and the aerodynamic drag (the latter can be neglected considering the extremely low vehicle speed), plus the addition of other contributions representative of the effects of soil compaction, bulldozing and other ground interactions. Eq. (1) explains all the above mentioned terms, where the F_{ri}'s are referred to the usual terms (respectively, rolling, slope, aerodynamic), while the F_{si}'s indicate the others (compaction, bulldozing, ground): as can be inferred from the proposed formulations, the additional terms are semi-empirical. All the used parameters are shown in Table 2. Further details can be retrieved from [16].

$$F_{\text{total}} = F_{\text{rR}} + F_{\text{r}\alpha} + F_{\text{rA}} + F_{\text{sC}} + F_{\text{sB}} + F_{\text{sG}}$$

$$\begin{aligned}
F_{\text{rR}} &= fMg\cos\alpha \\
F_{\text{r}\alpha} &= Mg\,\text{sen}\,\alpha \\
F_{\text{rA}} &= \frac{1}{2}\rho S C_x V^2 \\
F_{\text{sC}} &= b\left(\frac{k_c}{b} + k_\varphi\right)\left(\frac{z_0^{n+1}}{n+1}\right)C_c \\
F_{\text{sB}} &= b\left(0.67cz_0k'_{\text{pc}} + 0.5z_0^2\gamma_s k'_{\text{p}\gamma}\right)C_b \\
F_{\text{sG}} &= \frac{mg}{1000}\left(133 + \frac{2.5}{3.6}v\right)C_v
\end{aligned} \tag{1}$$

Additionally, the vehicle mass taken as a variable during vehicle operation, to take into account the effects of the bucket load.

Table 1
General characteristics of the hydraulic skid loader.

ICE	Cylinders	3
	Displacement (cm^3)	1116
	Max power (kW)	15.4
	Max torque (Nm)	66.5
	Fuel consumption* @ 1400 rpm (g/kWh)	255
	Fuel consumption* @ 2000 rpm (g/kWh)	255
	Fuel consumption* @ 2500 rpm (g/kWh)	265
	Fuel consumption* @ 2700 rpm (g/kWh)	320
Hydraulic System	Max pressure (bar)	180
Vehicle	Weight (kg)	1330
	Load capacity (kg)	330
	Size† L-W-H (m)	2.6
		1.1
		3.3
	Max speed (km/h)	7.5

* At full load.
† Max operative values.