

An Inclusive, System-Oriented Approach for the Study and the Design of Hydrostatic Transmissions: The Case of an Articulated Boom Lift

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ABSTRACT

When the designer's target is the optimization of a composite system, the analysis of the interactions between the different elements of the system becomes a crucial topic. As a matter of fact, in some cases, the effect of these interactions can become more important than the behavior of each individual component. In the area of fluid power, this problem is very common. In particular the case of hydraulic powered transmission for mobile applications can be considered a paradigm of these problems. This paper presents an original numerical approach to study and design of a hydrostatic transmission: the target is the optimization of the system as a whole, taking into account the characterization and the interaction among all parts. First, the system and the application are presented; the attention is focused on the analysis and modeling of its hydraulic parts (pumps, motors, valves). The potentials of the hydraulic model are enhanced showing how they are used for achieving an optimal design. Several solutions are compared in terms of performance (torque vs. speed) and efficiency, on the basis of numerical results. In the second part of the paper, the hydraulic model is integrated with the model of the combustion engine. In this case, the performance of the system can be calculated from a wider point-of-view, considering also the fuel consumed over user-defined duty cycles. In particular, the interaction between pump (primary unit) and combustion engine has a relevant effect on the system efficiency. Finally, the sub-system given by Internal Combustion Engine (ICE) and the primary unit is analyzed and optimized, considering engine speed and pump displacement as variable parameters.

INTRODUCTION

For many years engineers in the field of electro-hydraulic systems for mobile applications have traditionally approached vehicle transmission design in a segregated fashion, considering separately its main parts: combustion engine, hydraulic circuit and electronic control. However, because market competition has increased to such a high level, it has become almost impossible to improve upon many products (e.g. engines or pumps); and manufacturers have turned their focus toward an inclusive, system-oriented design approach. Subsequently, the word "system" has become a keystone for engineers and engineering companies world-wide as they work to improve performance and economy through system optimization, considering the effects of the subsystems' interactions.

The newly appointed position of "system engineer" to most manufacturing companies is more than adequate proof that the pursuit of comprehensive design procedures that increase the number of design variables and consider the behavior of the entire system instead of its individual parts is essential to future success and development. Also essential to this inclusive approach is the use of simulation, an invaluable tool that provides accurate evaluation of system performance when analyzing the interactions between two parts; for example, the hydraulic circuit and prime mover (usually a combustion engine) of a hydrostatic transmission (HT). In this case, as well as many others, optimization of the system control can only be achieved by using simulation to precisely dissect the relationship between the two subsystems.

This paper presents a detailed study of the drive system of an articulated boom lift. This project has been carried out in cooperation between Tigieffe s.r.l., an Italian manufacturer of Mobile Elevating Work Platforms (MEWPs), and the Fluid Power Group at the Industrial Engineering Dept. (IED) of the University of Parma. For this kind of machines the drive system is a closed loop hydrostatic transmission, powered by a Diesel engine. Both traction and lifting are controlled by electronic devices: the operator commands a joystick which communicates with a CPU board. The research was focused on two main topics: the first was the development of a simulation tool for the hydraulic system capable of predicting its operation for generic drive cycles. The second was the optimization of the entire hydrostatic transmission design, through the analysis of the interaction between the ICE and the hydrostatic units, in order to improve the overall efficiency during the most common working conditions. For these purposes, the authors built a numerical model of the system (HT, ICE and loads). The initial layout of the system was proposed by the company, yielded by their engineers' experience, which had been developed without the support of simulation. The authors proposed and analyzed alternative designs, comparing the system performance over different drive cycles. The design parameters and the control system have all been optimized by means of the numerical simulation tool.

THE HYDROSTATIC TRANSMISSION AND ITS NUMERICAL MODEL

Fig. 1 shows the ISO representation of the circuit initially proposed for the HT: one pump and four motors are

connected in a closed loop circuit [1-3]. The prime mover (MT) is a 2.6 dm³ Diesel ICE with a nominal power of 37 kW. The primary unit (P1) is an axial piston pump with proportional electronic control of the displacement (maximum of 63 cm³) [4]. As secondary units (M1-4), four axial piston motors [4] are connected to four wheel hubs (R1-4) which have the same ratio ($\tau = 50$).

The hydraulic motors have a dual displacement, controlling the pilot lines its value can be set to "full" (53 cm³) or "partial" (26.5 cm³). The motors are connected in parallel and supplied by two reversible flow dividers, one for the rear and one for the front axle. In this way, the differential lock for each axle is always guaranteed, even when the vehicle is driving on rough or uneven surfaces. The low pressure line is supplied by a charge pump (P2); its pressure level is set to 20 bars by means of a dedicated relief valve (RV1). Part of the system is placed on the vehicle turret (engine and pumps), the motors and the flow dividers are mounted on the chassis. The two parts of the system are connected by a rotating hydraulic joint so that the turret can continuously rotate by means of a hydraulic slew ring.

The control of the drive system can select one of three different configurations (as for the majority of vehicles of this kind):

- Slow speed: the engine speed is set in order to reach the maximum torque. The hydraulic motors are at full displacement;
- Intermediate speed: the engine works at maximum power, motors are at full displacement;
- Fast speed: the engine is at maximum power and motors at 50% displacement.

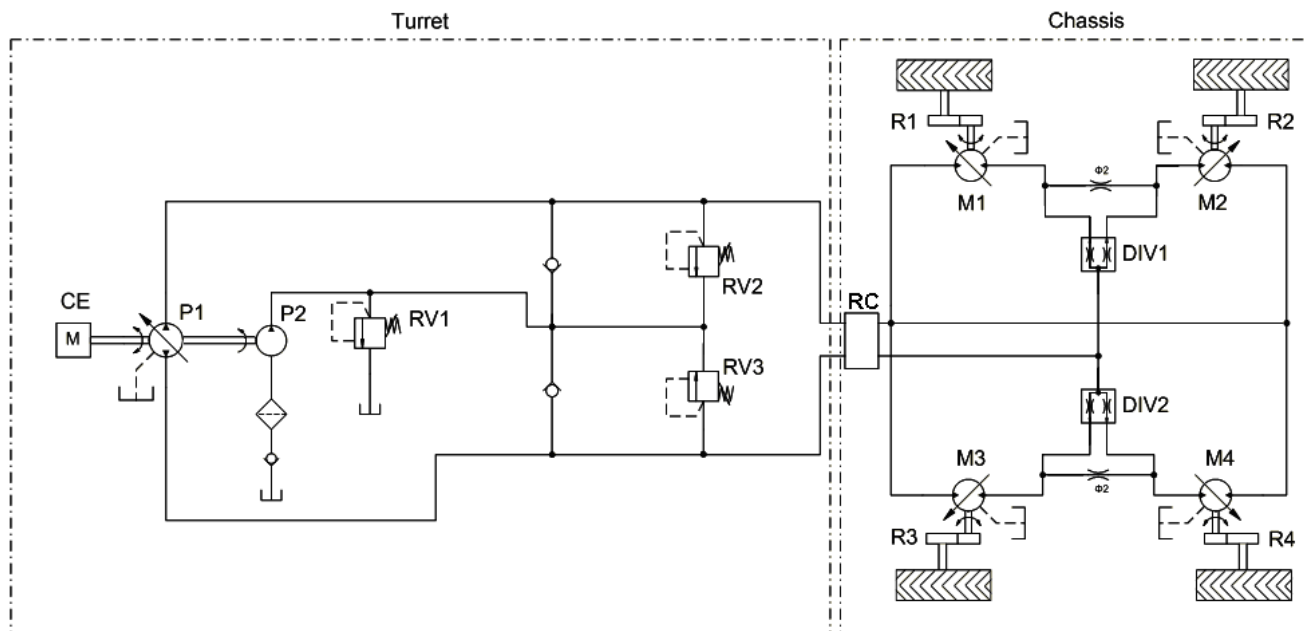


Figure 1 – Representation of the HT hydraulic circuit. ICE is the Diesel combustion engine, P1 the primary unit, P2 the boost pump, DIV1-2 the flow dividers, M1-4 the secondary units, R1-4 the wheel torque hubs and RV1-3 the relief valves.

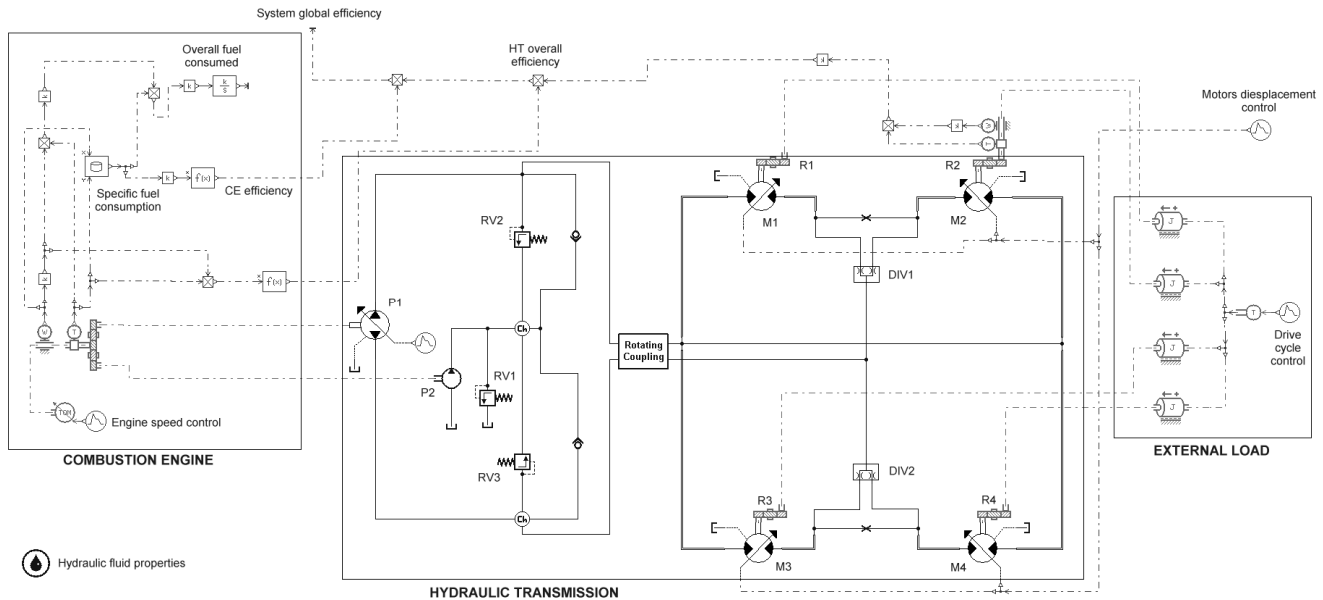


Figure 2 – Sketch of the AMESim simulation model. Components labels correspond to the hydraulic circuit of Fig. 1.

Table 1 – Description of the most significant icons utilized in the simulation model (icons refer to the sketch of Fig. 2).

icon	description	main equations
	Pump. This model is implemented by a combination of standard AMESim sub-models (see the sketch of fig. 3). In particular this model allows to predict the main pump variables (flow rates, pressures and shaft torque) accounting for volumetric and hydro-mechanical efficiency. These are calculated through interpolation of look-up tables, based on data provided by the manufacturer.	$Q_{out,P} = \eta_{V,P} \alpha_P V_{d,P} n_P$ $Q_{in,P} = \alpha_P V_{d,P} n_P$ $Q_{l,P} = Q_{in,P} - Q_{out,P}$ $T_P = \frac{\alpha_P V_{d,P} \Delta p_P}{\eta_{mh,P}}$ where $\alpha_P \in (0 \div 1)$
	Motor. Similar to the model of the pump, this model simulates the motor using a combination of AMESim standard sub-models. Look-up tables of volumetric and hydro-mechanical efficiency are used in order to predict the actual values of flows, pressures and torque.	$n_M = \frac{\eta_{V,M} Q_{in,M}}{\alpha_M V_{d,M}}$ $Q_{out,M} = \eta_{V,M} Q_{in,M}$ $Q_{l,M} = Q_{in,M} - Q_{out,M}$ $T_M = \eta_{mh,M} \alpha_M V_{d,M} \Delta p_M$ where $\alpha_M = 0.5$ or 1
	Rotating hydraulic joint. This model includes sub-models from the Hydraulic Resistance Library [6]. The purpose of the model consists in the calculation of the pressure losses, accounting for flow equations and experimental data reported in [7].	For each line: $\Delta p = \sum_i \xi_i \frac{\rho Q_i^2}{2 \Omega_i^2}$
	Reversible flow divider. This model simulates the behaviour of the component [8] through a combination of mechanical and hydraulic sub-models from the Hydraulic Component Design library [6] of AMESim® (fig. 4). The results provided by this model have been verified through comparisons with experimental data provided by the manufacturer. Authors dedicated a special attention to this component as far as it appeared to be playing a critical role in the HT operation.	See fig. 4 and [6] for equations
	Rotary load. This standard AMESim model (included in the mechanical library) is used to simulate the load at each motor. Its value depends upon the mass of the vehicle, the terrain properties and the slope. The contribution of friction (in terms of viscous friction, Coulomb friction and stiction) is also accounted.	