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Design of a hydraulic servo-actuation fed by a regenerative braking system ☆

L. Pugi [a,*], M. Pagliai [a], A. Nocentini [a], G. Lutzemberger [b], A. Pretto [c]

[a] University of Florence, DIEF MDM-LAB, Via Santa Marta 3, 50139 Firenze, Italy
[b] University of Pisa, DESTEC, Largo Lucio Lazzarino, 56122 Pisa, Italy
[c] GruppoPretto SRL, Via Cagliari, 2, 56038 Ponsacco, Italy

HIGHLIGHTS

- An innovative on board hydraulic system fed by a KERS is presented.
- A complete model of the proposed system is presented.
- The model is validated on experimental data.

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ABSTRACT

Many conventional truck and working machines are equipped with additional hydraulic tooling or manipulation systems which are usually fed through a mechanical connection with the internal combustion engine, involving a poor efficiency. In particular, this is a common situation for industrial vehicles whose mission profiles involves a relevant consumption of energy by the on board hydraulic systems, respect to the one really needed for only traction purpose. In this work it is proposed an innovative solution based on the adoption of a system aimed to recover braking energy in order to feed an efficient on board hydraulic actuation system. The proposed system is then adopted to a real application, an Isuzu truck equipped with a hydraulic tooling for garbage collection. A prototype of the system has been designed, assembled and tested showing a relevant improvement of system efficiency and the feasibility of the proposed approach. In the paper the proposed solution is presented, showing the simulation models and preliminary validation results including experimental devices assembled to perform the tests.

1. Introduction

1.1. Topic of the research

Many kinds of -industrial vehicles are usually designed and assembled as customized versions of commercial trucks equipped with electro-hydraulic tooling or manipulation systems devoted to perform specific operations required by the application. Typical applications are related to vehicles used for maintenance and services for urban centres such as garbage collection and other maintenance services as visible in Fig. 1.

Currently, most of these vehicles are conventional trucks with an internal combustion engine that is also used to provide the mechanical power needed to feed the board electro-hydraulic tooling and actuation systems.

Especially for vehicle devoted to perform urban maintenance services, the total amount of energy needed by on board hydraulic system is often relevant respect to the one needed for traction purposes mainly for two reasons:

- Overall travelled distances and mean speed of vehicle are quite low.
- Power required by the electro-hydraulic plant is relevant, and the way in which this power is generated and transferred by the internal combustion engine involve considerable amount of losses.

The aim of the work was the investigations of solutions able to substantially improve efficiency and performance of the vehicle including the on board electro-hydraulic servo-system proposing solutions that can be easily adopted not only for new vehicles,

☆ Servo-System fed by a KERS.
* Corresponding author.
E-mail address: luca.pugi@unifi.it (L. Pugi).

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Fig. 1. Example of vehicle modified isuzu P75 3.0, modified by Pretto SRL.

but also for the revamping of large fleet of conventional ones currently hold by public administrations.

For these reasons the installation of the proposed systems has to be, as much as possible, simple and also adaptable to different models of trucks.

Typical mission profiles, visible in Fig. 3, are associated to urban circuits in which the mean distance between two consecutive stops, where dumpsters have to be collected is few hundreds of meters and the maximum speed is usually not over 50 km/h in order to respect urban speed limits. At every stop, the typical time needed to perform the required operations is usually comprised between 40 s and few minutes.

In conventional vehicles electro-hydraulic plant is fed by the internal combustion engine of the truck so it cannot be switched off during a stop involving an increment of fuel consumption and pollution. In particular, in a mission of about 10 h about 100 stops with a mean duration of around 80 s are performed. So the introduction of this system should assure that the motor can be switched off for at least 2 h, and 20 min which represent at least the 20–22% of the duration of the entire mission. Also it should be considered that garbage collection in urban centres is often performed during the night so a significant reduction of the acoustic emission due to the switching off of the internal combustion engine is highly desirable. These data have been obtained by monitoring with an on board GPS localization system the typical behaviour of a truck performing garbage collection in the town of Livorno, Italy.

Considering the over cited mission scenario, authors proposed to fed the electro-hydraulic plant of the vehicle through the electrical energy stored in the battery, which is continuously recharged exploiting the energy recovered during the braking manoeuvre according the scheme of Fig. 2.

Due to the encumbrance and cost limitation, it is fundamental to minimize cost and sizing of the energy storage system and of the adopted electrical machines and converters.

As a consequence, a non-secondary task of the activity was also a critical redesign and simulation of the hydraulic plant in order to maximize its efficiency respect to the current solution with affordable costs and intervention respect to the design of conventional plants that have to be modified and "revamped".

1.2. State of the art

For which concern the state of the art there is a wide literature concerning the adoption of electric or hybrid systems able to recovery the kinetic energy during the braking phase. Particularly for the design of hybrid and ground vehicles, this matter is so widely discussed that authors should cite only some review papers as the one of Hannan [1] or Mierlo [2], able to roughly summarize possible solutions.

Also Authors have some previous experience in the development of a full electric vehicle with four in-wheel drive motor [3] and more generally on energy recovery during the braking applied to railway systems [4,5].

Looking at works concerning the life prediction of batteries like the one of Onori [6], it should be noticed that in order to increase life and reliability of accumulators, it is very important to reduce the amplitude of charge and discharge cycles in terms of currents, thermal loads and depths of discharge. In particular authors have focused their attention on works concerning life estimation of Lithium-Ion and Lithium Polymer batteries which are currently the most commonly used for these kind of vehicle applications. For this reason also authors have found interesting contributions and references in many works concerning the estimation of the state of health of batteries using different techniques ranging from impedance measurement [7] to smart filtering of current/power measurements [8,9].

As a consequence, authors have focused their attention to the optimization of the power consumption of the on board servo-hydraulic systems which is the object of many recent publications. In particular looking at review paper concerning this topic authors have found that general reviews on improved efficiency of hydraulic servo-system focused their attention on various way to perform the so called "Pump Control" [10]: speed of actuators is controlled by generating only the oil flow exactly needed for the motion to be performed, minimizing as much as possible laminated and dispersed flows.

This kind of regulation is often called pump control, since the value of generated oil flow is regulated acting on the rotation speed of the pump (fixed displacement pump) or modifying pump displacement (variable displacement pump). In particular a good and very recent review on this matter is represented by the works of Zhongyi Quan [11] and Aly [12].

In particular, the conversion of a wide variety of existing servo-hydraulic machines to pump controlled system is still matter of recent research. One of the most investigated case of application of hydraulic pump is represented by the study of hybrid electro-hydraulic excavators [13–15].

A more extended approach to the general problem of converting an heavy duty vehicle to an hybrid "series" or "parallel" solutions with pump controlled actuators is studied in the work of Ponomarev [16].

However, as visible in the scheme of Fig. 4, the general solutions proposed in the work of Ponomarev, involve the usage of at least $n + 1$ electric drives (including machines and converters) where n is the number of degree of freedom controlled by electro-mechanical actuators: in particular a dedicated machine is used to produce electrical energy from the mechanical power produced by the internal combustion engine and each degree of freedom (power conversion) is independently controlled by a dedicated electric actuator (performing pump control). More generally despite to the continuous improvement of electric systems, there is still a wide attention to the optimization of vehicle-fluid servo-system even for traction purposes as in the recent work of Shi [17] which is still focused on the development of hydro-pneumatic systems.

Another general trend in literature to which this work should be reconnected is represented by the investigation of hybrid system in which the energy consumed by an hydraulic plant is provided by a source which is renewable: as example in the work of Campana [18] where is considered the application of renewable sources to a pumping station for agriculture.