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**Title:**
# A Survey on Negative Control Architectures for Hydraulic Excavators

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## ABSTRACT

The present survey is one step of a complex research activity, directed toward the conception of innovative solutions for hydraulic directional control valves for excavators of the 20-ton category.

In the world scene, as far as the hydraulic circuit present in this type of machines is concerned, a wide diffusion of the Negative Control and Positive Control architectures is observed; in literature it is also possible to find "hybrid" configurations that try to optimize system operation by taking advantage of the peculiarities of the above mentioned architectures.

Although the mechanical structure of the excavators is practically standardized among the different manufacturers, interesting solutions and configurations are adopted in the implementation of the directional control valve.

The present work aims to analyze and describe the common features observed in some of the commercial devices for the Negative Control architecture, starting from their basic structure (i.e. layout and number of sections), to get to the study of internal regenerations and external confluences (or junctions).

In order to understand, in detail, the characteristics of some constructive choices (common and not, between the manufacturers), a full excavator model was implemented in the AMESim simulation environment, that includes a complex directional control valve, actuators and a 3D mechanism with 9 degrees of freedom representing the excavator's kinematics.

By means of the simulation model, using the relevant JCMAS standards as a guideline for representative working cycles, a qualitative analysis of system operation is carried out, with a particular focus on multiple actuations (complex movements).

**KEYWORDS:** Excavators, Directional Control Valve, Negative Control, Negative Regeneration, Confluences, Complex movements.

## INTRODUCTION

According to [1] the term "hydraulic excavators", refers to the following machine type:

*"self-propelled machine on crawlers, wheels or legs, having an upper structure capable of a 360° swing with mounted equipment and which is primarily designed for excavating with a bucket, without movement of the undercarriage during the work cycle"*.

However, under this unique definition, for each manufacturer, it is usual to find a wide family of machinery, that, based on the weight, is subdivided in MINI, MEDIUM and LARGE excavators. Although the primary functionality of excavation is the same (as well as the overall appearance), for the different sizes of machine, there are considerable differences in the structure of the hydraulic circuit.

Starting from a previous analysis [2] and focusing the attention on excavators of the 20-ton category, a wide diffusion of the Negative Control and Positive Control architectures is observed ([3-5]) with regard to the hydraulic directional control valves. Whilst in [2] the Negative Control architecture was studied, together with other common architectures (viz. Constant/Variable Pressure, Load Sensing, Positive Control and Open Center), in terms of intrinsic characteristics, analyzed for a reference case given by a single actuation, the present survey aims to analyze, for the Negative architecture alone, the constructive choices and some arrangements developed to maximize the performance of the system (some of which are described e.g. in [6-14]).

## THE NEGATIVE CONTROL ARCHITECTURE

Directional control valves for excavators are commercial products for which manufacturers provide poor if any documentation; whilst searching through patents, there is an actual world (featuring Japanese and Korean manufacturers) of mechanical/electronic solutions, where the "base structure" is modified to improve machine operation.

Neglecting for a moment the spool profile, the base structure in a hydraulic Negative Control architecture, as shown in Fig.1 is an Open Center[1] system requiring, in addition, only a measurement orifice placed on the bypass line at the end of the whole directional control valve block. This orifice is placed in parallel to a pressure relief valve (their union is usually indicated as "Negacon") and when a main spool is being moved out of the central position (with a displacement directly proportional to the pilot signal), the neutral line closes and the resulting pressure at the Negacon drops.

The hydraulic element strictly responsible for the generation of control pressure $p_N$ is the orifice, which is the only one necessary (and active) in steady state condition; however, to prevent improper pump displacement demands during operator command transients, the relief valve is added, to clip possible pressure spikes.

As shown in Fig. 2, the pump regulation characteristic and the flow rate characteristic are described by the following equations:

$$\alpha=\alpha(p_N)$$

$$Q_{PUMP}=Q_{MAX}*\alpha(p_N)$$

where $\alpha$ is the pump displacement setting, $Q_{PUMP}$ is the pump delivery flow, whose maximum value (at full displacement) is $Q_{MAX}$ and $p_N$ is the pressure drop across the measurement orifice, which controls the pump so that the displacement decreases as the pressure increases.

Figure 1 shows the simplest purely hydraulic setup, where the pump is directly piloted by $p_N$; in more complex solutions $p_N$ is furtherly processed by electronically controlled electro-hydraulic stages, allowing the implementation of variable fine calibrations (e.g. as a function of machine operating point and operator settings).

In Fig. 2 the pump delivery flow ($Q_{PUMP}$) and the flow through the orifice ($Q_{NEGACON}$) are plotted, along with the pump setting ($\alpha$), as a function of $p_N$. In standby condition:

$$Q_{PUMP}= Q_{NEGACON}$$

therefore the system has its equilibrium point in $P_{RES\_0}$.

Considering one valve section, as the spool moves away from the central position, part of the pump flow is supplied to the load (actuator): $P_{RES\_0}$ splits in two points ($P_{RES\_1}$ and $P_{RES\_2}$), that move, in the left direction, on the two flow curves, until the bypass line is completely closed and the entire flow is directed to the actuator.

Looking at the structure of an excavator, six main actuators can be found (Fig. 3), subdivided as follows: two jacks for the movement of the boom (one in case of small vehicles), one jack each for the arm and the bucket, two hydraulic motors for the vehicle translation (travel left and travel right tracks) and finally one hydraulic motor for the rotation of the turret (swing).

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[1] As implied by the "open center" definition, when the system is in standby condition, machine in standstill and no command from the operator, a minimum "flushing" flow rate is always allowed (on the bypass line).

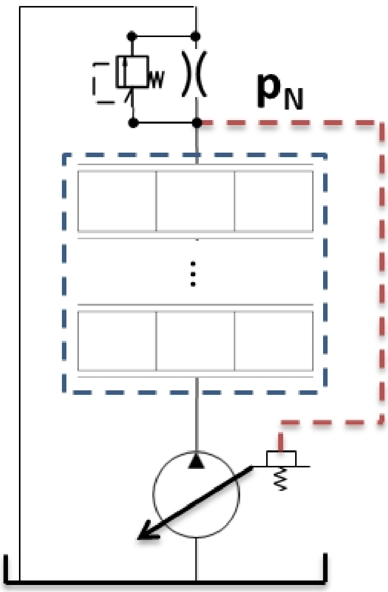

**FIGURE 1.** NEGATIVE CONTROL SYSTEM

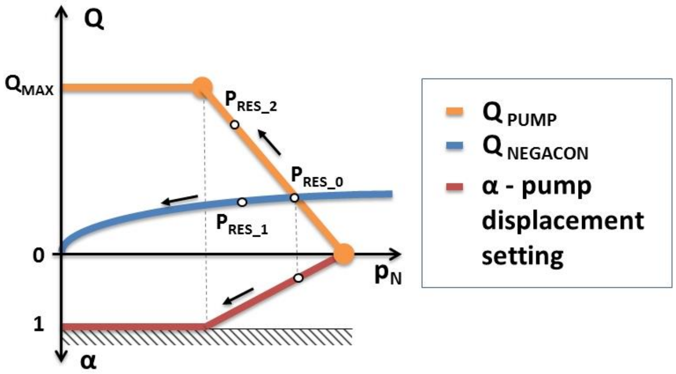

**FIGURE 2.** OPERATIVE CHARACTERISTIC

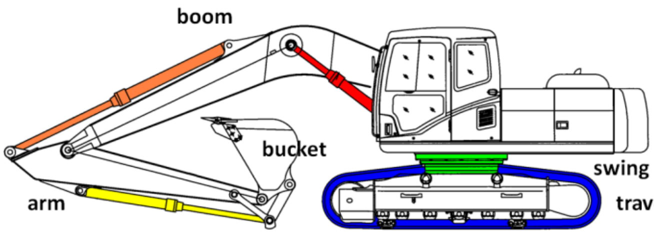

**FIGURE 3.** HYDRAULIC EXCAVATOR

Considering the category of machines of interest (approximately 20 ton), the structure of a directional control valve for the Negative Control architecture is outlined in Fig. 4.

An example of an actual commercial valve is shown in Fig. 5. The single-piece physical structure probably poses the biggest constructive difficulty, since what can quite easily be obtained by stacking individual section elements, becomes very demanding in a single-block melting process.

The component is divided in two main blocks (left and right), each of which supplied by an individual variable displacement pump ($P_1$ and $P_2$) and composed by multiple sections (as in Fig. 4).

Leaving aside for the moment the “straight travel” section (whose operation is described below), the names of the sections are self-explanatory. It can be seen that for the actuation of both the boom and the arm two sections are provided, allowing supply flows from the two pumps to converge (internally or externally) to the actuator.

An optional section is also present, used for example for handling the blade.

This layout, being by far the most common, is taken as reference; nonetheless it is possible to find different orders in the placement of the sections, depending on specific requirements by the machine manufacturer.

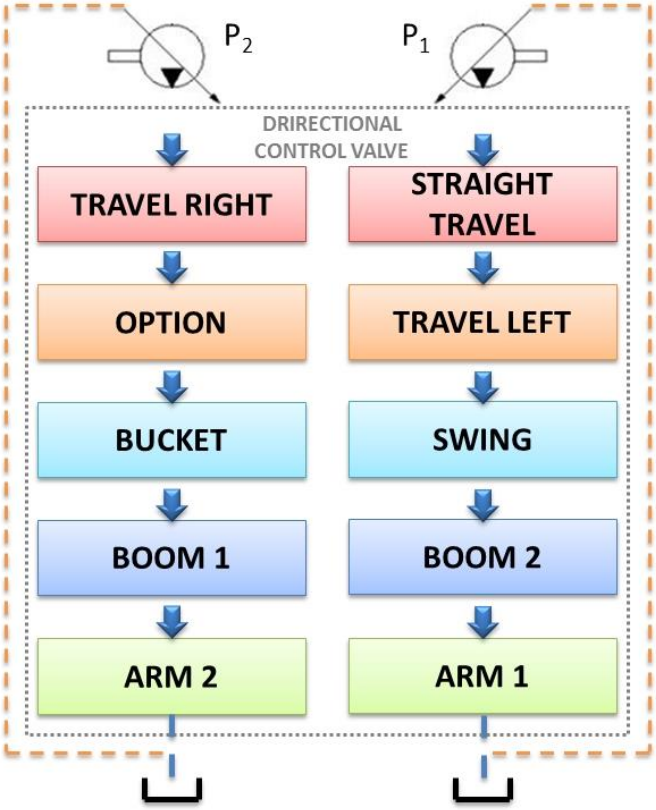

**FIGURE 4.** DIRECTIONAL CONTROL VALVE LAYOUT

To increase the vehicle efficiency and ensure proper operation, the manufactures implement circuital solutions that have become a “de facto” standard for the analyzed architecture.

**FIGURE 5.** EXAMPLE OF DIRECTIONAL CONTROL VALVE FOR 20~32-TON EXCAVATORS (PARKER MOBILE CONTROL DIVISION ASIA – AV 280)

Below some of the solutions, that are considered among the most significant and widespread, are discussed. The analysis was carried out with the aid of numerical simulation in the AMESim environment; the main parameters used in the model are listed in Tab. 1.

**TABLE 1.** MODEL PARAMETERS

| Parameter | Value |
|---|---|
| Total excavator mass | 20 [t] |
| Engine speed | 2000 [rpm] |
| Pump 1 max. displacement | 100 [cc/rev] |
| Pump 2 max. displacement | 100 [cc/rev] |
| Max. operating pressure | 350 [bar] |

Being the main focus on the hydraulic directional control architecture, the model includes the following simplifications:

- The engine is modelled as an ideal rotational speed source (i.e. with unlimited power capability), therefore all energy-related analyses were carried out on the hydraulic side of the system;
- For all hydraulic pumps and motors, constant efficiencies are assumed.

### Straight travel

As shown in Fig. 4, the two pumps deliver flow to the respective blocks (left or right); however, the “routing” of the supplied flow is changed in case of multiple actuations that implement simultaneously travel (left and/or right track) and at least one of the other users.

Basically “straight travel” does not indicate a section that supplies an actuator, but an auxiliary 4-port 2-position hydraulic valve (see Fig. 6). For the two valve positions, the flow paths are:

- From $P_1$ to A and from $P_2$ to B in the right-hand position (not commanded)
- From $P_1$ to B and from $P_2$ to A in the left-hand position (commanded)

For the sake of simplicity, the control logic generating the pilot signal for the straight travel valve is represented in Fig. 6 by means of logic ports (actually, the command is hydraulically implemented).

When the valve is not commanded (direct flows) each pump supplies one section, as indicated in Fig. 4, while, when the valve is commanded (cross flows), pump P1 supplies both GROUP 1 and GROUP 2, while pump P2 supplies travel left and travel right sections (“GROUP 1” is the set composed by swing, boom 2 and arm 1 sections, while “GROUP 2” includes the remaining sections: bucket, boom 1 and arm 2).

With this “simple” valve and control logic, the manufacturers can ensure controllability and feasibility of the translation in presence of other actuations and in every load condition (both resistant and dragging).

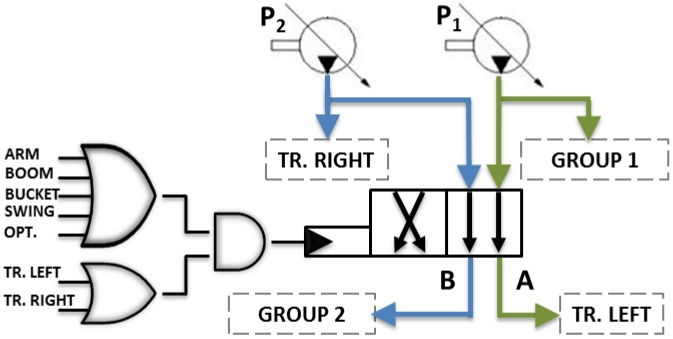

**FIGURE 6.** STRAIGHT TRAVEL STRUCTURE (IDLE STATE)

## Negative regeneration

Let's start by providing a definition of "negative regeneration": in the case of gravitational load (dragging), all or part of the outgoing flow rate from the jack (directed to the tank) is redirected back to the jack supply, in order to increase the input flow rate. The purpose in not to increase the actuator speed (as in "regular" regeneration), but to recuperate gravitational energy, thus avoiding to deliver excess flow rate and increasing system efficiency.

To describe the operating mode for the regenerative paths, below, a complete cycle of the boom is examined; let's suppose, therefore, that the excavator has the boom completely down (jacks retracted), brings it up to its full extension (jacks completely extended) and then back to the initial condition. In the first phase, denoted as "boom up", there is no regeneration and both sections, boom 1 and boom 2, are commanded (see top side of Fig. 7); through an internal connection the supplied flows join and feed the bottoms of the jacks.

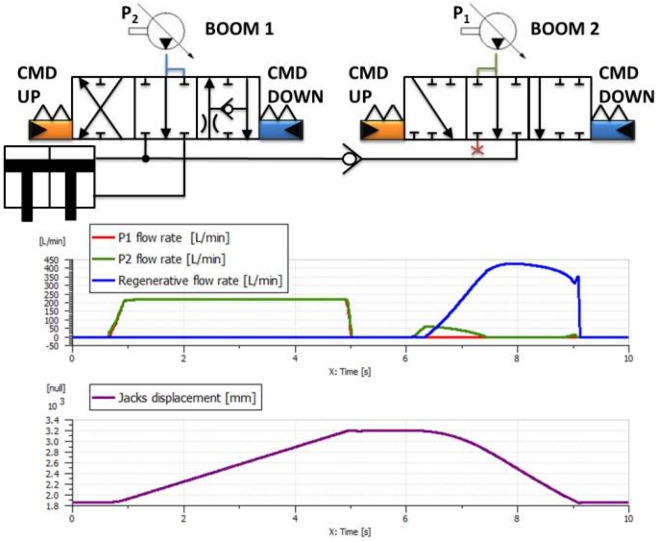

**FIGURE 7.** BOOM UP & DOWN OPERATION

During the second phase, denoted as "boom down", where the load is normally dragging, only the boom 1 section is activated (pump P1 doesn't contribute in any way to the movement). In this second case, as highlighted by the AMESim model (bottom of Fig. 7), it can be seen how part of the flow, which would otherwise go to discharge, is actively used for the movement of the actuators.

A similar structure can also be found for the arm sections; during the "arm dump" operation the section flow rates (from arm 1 and arm 2) simply converge; during the "arm crowd" operation the section flow rates converge and in the arm 1 section is fitted with a regenerative path.

## External junctions

Analyzing the single section of the bucket, in some cases, it is possible to find an external junction between the two valve blocks; to illustrate this possibility a bucket-only cycle is considered. Let's suppose that the bucket is completely open (jack extended), moves and closes completely (jack retracted), and then goes back to the initial condition.

In the first crowd phase, when the bucket carries out the maximum workforce, simultaneously, in the other block (where no section is commanded) a variable orifice, located upstream of the Negacon, is controlled (see top side of Fig. 8). In this way, the displacement of pump P1 increases and its delivery flow, through an external tube, supplies the bucket section (external confluence).

In the bottom of Fig. 8, while the jack is going out, it is possible to see the two different flow rates, supplied by pump P1 and pump P2, that enter in the active section. In the same figure, during the second phase, when the required force to the actuator is lower, it is visible how only pump P2 supplies the bucket section.

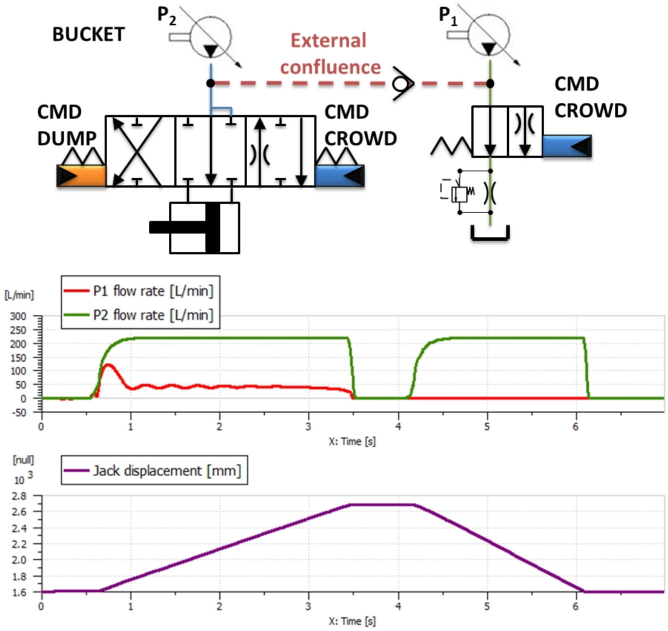

**FIGURE 8.** BUCKET CROWD & DUMP OPERATION

### Priority

Until now single-user cycles have been analyzed, now multiple actuations (complex movements) are considered, in which the use of both fixed and variable orifices that implement a priority between different sections is highlighted.

The first case of complex movements is moving up the boom and crowding the arm (as indicated in [15]: Grading-(levelling)-the-ground simulating motion without moving earth) and then bringing them back to the initial condition. In this case, where normally there are significant differences between the loads (consequently different actuator speeds), a priority for the boom is obtained by means of a fixed orifice placed upstream on the arm section supply (Fig. 9, left side).

A second example is a simultaneous command for boom up and bucket (both crowd and dump): a control valve with a variable orifice is placed on the bucket supply line, giving, once again, priority to the boom. In this case though, the orifice modulation is directly proportional to the boom up command, implementing a dynamic priority scheme (Fig. 9, right side).

Obviously, the previously described priorities are not exhaustive of all the possibilities. A comprehensive analysis [3] was carried out on several commercial products, where the architecture of each directional control valve is schematized from a functional perspective, in the form of a block diagram, highlighting the sequence, the relative priorities, and the connection layout of the individual sections.

As an example, the architecture shown in Fig. 10 involves the use of three different variable orifices, so that:

- The boom section has higher priority than the bucket section;
- The boom section has higher priority than the swing section;
- The swing section has higher priority than the arm section.

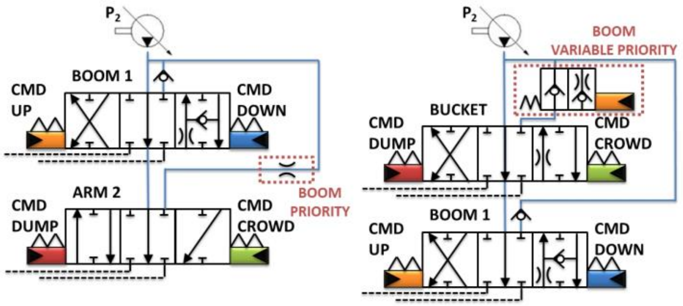

**FIGURE 9.** FIXED & VARIABLE BOOM PRIORITY

**Future developments**

The current AMESim model will be initially improved by including actual mechanical and volumetric efficiency maps of hydraulic pumps and motors, for more accurate (quantitative) analyses. Engine fuel consumption and torque/power maps will then be implemented, allowing to extend energy efficiency investigations to the full system.

Furthermore, in view of the foreseen constant increase in the usage of electronic control in construction machinery, control logic will be added to the model, by means of a Simulink-AMESim co-simulation framework (as described e.g. in [16]) and relevant related aspects (like e.g. benefits of integrated whole-machine control, performance of advanced control schemes, functional safety) will be investigated in model-in-the-loop simulations.

The above mentioned new controls will range from a simple electronic “re-modulation” of the Negative Control pressure signal to complex “hybrid” schemes (i.e. borrowing features from both the Negative and the Positive Control concepts), processing also the operator actuation command signals, to achieve an improved performance in terms of optimized multiple actuations.

Model-based development of the control in Simulink, automatic code generation and virtual prototyping in the co-simulation framework are expected to lead, in a relatively short time, to possible prototype ECU implementations of the most promising control schemes.

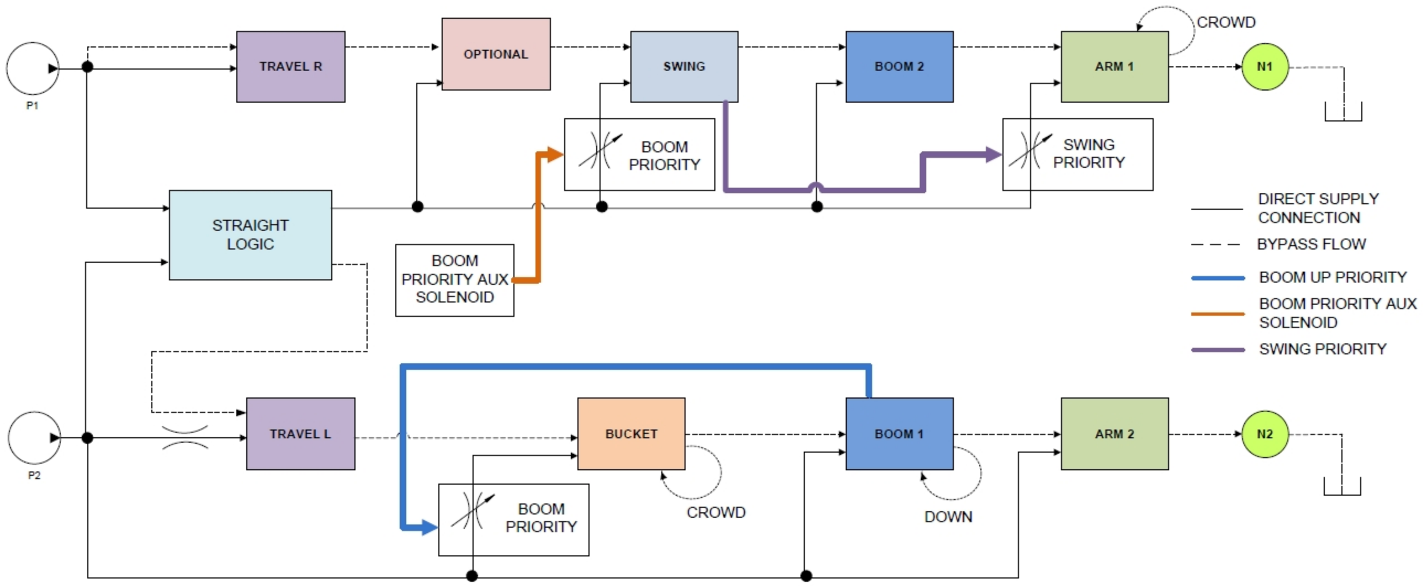

**FIGURE 10.** EXAMPLE OF FUNCTIONAL BLOCK DIAGRAM ANALYSIS OF A NEGATIVE CONTROL DIRECTIONAL CONTROL VALVE [3]

## CONCLUSIONS

A reference directional control valve structure was identified, to represent a typical Negative Control architecture, widespread in today's world scenario for the 20-ton hydraulic excavator class.

Starting from a base architecture (providing a straight travel section, two sections for boom and arm and one section for each of the other actuators), common elements were observed in different commercial devices, like internal regeneration, external confluence, fixed and/or variable priorities between two sections (in case of complex movements), aimed to ensure proper and efficient system operation, at the cost of a considerable constructive difficulty in a single-block melting process.

The qualitative analysis carried out in the present work confirmed the effectiveness of the considered features. Nonetheless, driven by the constantly increasing interest in electronic solutions, several manufacturers have been investigating for years now possible modifications or improvements to this "base solution", examples of which are "hybrid" architectures (borrowing elements from different standard architectures) and electronic management of specific subsystems (viz. operator command input interface, actuation of valve sections, pump displacement control).

A further improvement is expected from the implementation of whole-machine integrated electronic controls. A Simulink-AMESim co-simulation framework was conceived as the proper environment to test, compare and rapidly prototype promising innovative control schemes

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## REFERENCES

[1] International Standard ISO 6165 (2012): Earth-moving machinery – Basic types – Identification and terms and definitions

[2] Gessi S., Martelli M., 2012, "Comparative Analysis on the Main Architectures for Hydraulic Mobile Machines", Proceedings of the 7th FPNI Phd Symposium On Fluid Power, Reggio Emilia, Italy. ISBN: 978-88-7559-069-7

[3] Martelli M., Gessi S., Zarotti G. L., 2011, "Analisi preliminari su distributori oleodinamici di tipo Positive/Negative Control" (EN: "*Preliminary analysis of hydraulic Positive/Negative directional control valves*"), Italian National Research Council (CNR) internal report, ID 293086

[4] Martelli M., Gessi S., Zarotti G. L., 2012, "Comandi oleodinamici per Escavatori (circuiti fondamentali)" (EN: "*Hydraulic controls for excavators (basic circuits)*"), Italian National Research Council (CNR) internal report, ID 293088

[5] Martelli M., Gessi S., Zarotti G. L., 2012, "Piattaforma Simulativa per Escavatori (circuito dimostrativo)" (EN: *Simulation Platform for Excavators (demonstrative circuit)*"), Italian National Research Council (CNR) internal report, ID 293091

[6] US Patent: US 7,430,859 B2. 2006. Fluid pump control system for excavators. Assignee: Doosan Infracore Co., ltd., Ichon (KR)
[7] Japanese Patent: JP2010047984A. 2010. Hydraulic circuit of hydraulic excavator. Assignee: Sumitomo (SHI) construction machinery co ltd
[8] Japanese Patent: JP2010169204A. 2010. Hydraulic circuit for hydraulic working machine. Assignee: Caterpillar Japan ltd
[9] Patent KR20030008069A. 2012. Hydraulic pump for construction machinery. Assignee: Volvo construction equipment ab
[10] Japanese Patent: JP2009167618A. 2009. Hydraulic circuit of hydraulic excavator. Assignee: Caterpillar Japan ltd
[11] Japanese Patent: JP2006144851A. 2006. Controller of fluid pressure circuit, method of controlling the same, and work machine. Assignee: Shin Caterpillar Mitsubichi ltd
[12] Japanese Patent: JP2006103893A. 2006. Negative control circuit for industrial machine. Assignee: Caterpillar Japan ltd
[13] Japanese Patent: JP11230105A. 1998. Positive steamflow control device. Assignee: Caterpillar incorporated
[14] Korean Patent KR20090069696A. 2007. Controllability improvement apparatus for construction machinery. Assignee: Doosan Infracore CO ltd
[15] Japanese standard JCMAS H 020 (2010) – Earth-moving machinery – Test methods for energy consumption – Hydraulic excavators. Japan Construction Mechanization Association
[16] M. Martelli, S. Gessi, E. Tonini, 2013, "Model-Based Development of Safety-Relevant Electronic Control Systems for Agricultural Machines", Proceeding of the 7th Americas Conference of the ISTVS, Tampa, Florida, USA. ISBN: 978-0-9838742-2-5