Optimal System Solutions Enabled by Digital Pumps

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ABSTRACT

This paper will outline mobile equipment system solutions which are enabled by the newly emerging technology of digital hydraulic pumps and digital hydraulic motors. While similar in some aspects to conventional hydraulic machines, digital hydraulic pumps and motors have several key features which enable system efficiencies and control unprecedented in the world of hydraulics. Benefits include:

- Measured 25% fuel savings vs. traditional hydrostatic transmissions without use of energy storage.
- Increased machine productivity, or potentially significant engine downsizing.
- Superior overall efficiencies throughout the displacement range.
- Extremely fast and stable dynamic response for excellent machine controllability.
- One system controls the main vehicle functions allowing optimal use of the engine torque limit.
- Internal flow sharing capability; multiple services can be supplied by a single pump. The system controller can dynamically allocate pump/motor displacement as required by the duty cycle; allowing greater utilization of the installed capacity.
- Loads can be applied to the engine under the full control of the system controller; and thus the engine can also be operated at the most efficient point.
- Software configurable drive performance.

This paper will further discuss the machine architectures and duty cycles which take advantage of the benefits of digital hydraulic pumps and motors.

INTRODUCTION

The technology field of digital hydraulic systems has been gaining significant prominence and momentum over the last decade. There are many compelling reasons for this recent advancement.

Mobile vehicle systems for both propel and work functions are being pushed to be more productive, to minimize the total installed cost for the OEM, and to reduce the total cost of ownership. Furthermore, legislation continues to challenge vehicle manufacturers in terms of emissions regulations, operator comfort, noise and safety; trending towards future constraints in terms of fuel economy and/or CO2 emissions; cradle to grave lifecycle planning, and others. While the volatile cost of energy continuously threatens end-users, an increasing focus is required on a system level to best match components and sub-systems to eliminate as many losses as possible while keeping the bar high in terms of vehicle performance.

The emergence of digital hydraulic pumps and motors into the global marketplace brings much needed innovation to bear against these issues.
DIGITAL HYDRAULICS

The terms ‘digital’ and ‘hydraulic’ have been associated with one another in many different contexts over the last several decades; Juhala\(^1\), Merrill\(^2\), Linjama\(^3\), Bishop\(^4\). Thus, for clarity in this paper, the scope of digital hydraulic pumps and motors will be limited to ones similar in type to those currently under development by Artemis Intelligent Power. We will use the terms ‘DDP’ or ‘digital pump’ to refer to Digital Displacement® Pumps and ‘DDM’ or ‘digital motors’ in reference to Digital Displacement® Motors. More detailed description of these types of machines will follow in the next sections.

Digital pumps and motors distinguish themselves from conventional pumps and motors in how they achieve variable displacement and how they commutate individual pistons/cylinders between the low and high pressure ports.

In conventional piston-type hydraulic pumps and motors, fluid commutation is accomplished by a valve plate (also port plate) which is optimized for the best efficiency and noise at one specific operating condition. Variable displacement is accomplished by changing the stroke of the pistons mechanically and/or hydraulically.

In contrast, the pistons in digital pumps and motors maintain a constant stroke regardless of effective displacement. They accomplish both commutation and variable displacement by electronically controlling an inlet and outlet valve at each cylinder in a phased relationship to crankshaft position. Thus, a relatively simple and robust (typically radial piston) machine with naturally low losses can be merged with an elegant control system and high speed on-off valves to achieve superior component level efficiency and controllability. Figure 1 shows a simplified schematic of a single digital pump or digital motor piston/cylinder and associated valves.

**Figure 1: Simplified Schematic: Digital Pump/Motor Piston/Cylinder**

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COMPONENT FUNCTION

Digital hydraulic machines take several forms in order to provide the most appropriate functionality for specific machine sub-system requirements.

In its most basic form, a digital pump naturally operates as a variable displacement open circuit pump; analogous to an open circuit variable displacement axial piston pump. It thus has a tank port and a high pressure port and can deliver flow only out of the high pressure port: a single quadrant (flow and pressure) machine. See Figure 2.

**Figure 2: Digital Pump (DDP)**

A digital pump/motor then expands upon this functionality to include the ability to receive flow from a high pressure source (motoring mode). The machine still only has a P and a T port; so the addition of this motoring mode makes this machine analogous to a variable open circuit pump which can go ‘over-center’ – reversing the direction of flow. Thus, a second quadrant of operation is possible in flow and pressure. See Figure 3.

**Figure 3: Digital Pump/Motor (DDPM)**

The DDPM is well suited for sub systems where the shaft is driven by a prime mover. For applications (i.e. vehicle propel) which require starting of the digital displacement pump/motor from zero speed, a variant of the digital pump/motor is a better choice: the digital motor (DDM). The digital motor utilizes additional internal functionality to allow starting from zero shaft speed at high torque.
Connecting a digital pump/motor and a digital motor with a single high pressure line yields a shaft to shaft transmission with full four quadrant operation in speed and torque as shown in Figure 4. The pump/motor driven by the engine can provide or receive high pressure flow to match the demand of the digital motor connected to the final drive assembly. This final drive digital hydraulic motor can be commanded to provide positive or negative torque when spinning in either direction. This arrangement also naturally allows the integration of hydraulic energy storage in the high pressure line to allow energy recovery and reuse; Rydberg5).

![Figure 4: Full Digital Hydraulic Transmission](image)

Of course, there are many other arrangements of digital pumps and motors which are attractive when choosing an appropriate balance between cost/complexity and realized benefit. One such arrangement is the use of a digital pump or pump/motor on the input side of the transmission, and the use of a conventional closed circuit hydraulic motor on the output. See Figure 5. This arrangement does require the use of conventional valves to properly mate the P & T port of the digital pump or motor with the A and B ports of the conventional hydraulic motor. However, even with the required addition of direction and braking valves, this machine architecture offers a considerable fuel savings benefit.

![Figure 5: Digital Pump/Motor with Conventional Hydraulic Motor](image)

Another interesting possibility with digital pumps and motors involves the elimination of proportional valves between the hydraulic pump and the load. Often dubbed ‘direct-cylinder-control’, this architecture is possible due to the extremely fast and stable response characteristic of this type of hydraulic machine as shown in Figure 6. The often significant throttling losses, otherwise associated with the proportional valves, can be eliminated in this arrangement. Precise open loop position control of hydraulic actuators can also be achieved.

![Figure 6: Direct Cylinder Control](image)

As shown in Figure 7, with the simple addition of a hydraulic accumulator on the outlet port of a digital pump/motor, a very useful module is created which can store either excess energy available from the engine, or store energy from the rest of the machine from braking energy or load lowering; energy which would otherwise be wasted into heat. A significant portion of this energy would then be available for reuse by the machine.

![Figure 7: Energy Storage Module](image)

**MULTIPLE SERVICES**

An example machine architecture is roughly represented in Figure 8. This arrangement is typical of many mobile machine architectures; consisting of two main power consumers: propel and working functions. In this common arrangement, the engine power is split by a gear box which is commonly integrated into the transmission itself. The work function hydraulics and propel transmission arrangement are sized separately according to their individual requirements.
Figure 8. Typical Mobile Machine Layout

An alternative arrangement for this same vehicle utilizing digital pumps and motors is shown in Figure 9. Because the flow from individual pistons/cylinders in digital hydraulic pumps and motors are controlled independent of one another; another degree of freedom exists for the system designer when choosing how to combine these flows into net output flows.

Figure 9. Alternative Mobile Machine Layout

Thus, a single pump assembly can serve multiple consumers. Linjama Th) The working function and propel requirements can now be considered together, when sizing the entire system, to capitalize on synergies between the two. For instance, if the machine duty cycle has periods of high flow requirement for the propel service (driving near maximum speed for example) while the working function has relatively low flow requirements (i.e. small adjustments in hydraulic cylinder position), then a portion of the working function pump displacement can be directed to the propel service. This puts more pump displacement where it is most needed; allowing the engine to reduce its speed for a given flow demand, consuming less fuel. And, this allows the system designer, understanding the collective needs of the entire machine, to minimize the total installed pump displacement. This, in turn, helps keep the installation package size and costs low.

**COMPONENT EFFICIENCY**

Focusing on the digital pump functionality, some general comparisons to typical conventional hydraulic machines can be helpful to quantify the potential benefit. Referring to Figures 10, 11, and 12, overall efficiency is plotted on the left y-axis, and power losses on the right y-axis. All plots refer to operation at 300 Bar; with a maximum input power condition of 175kW.

Figure 10: 100% Displacement

Figure 11: 20% Displacement

Figure 12: 1500 RPM

The figures clearly show the inherent component level efficiency gains / loss reductions that can be realized.
through digital hydraulic machines over conventional variable piston pumps and motors. The most significant improvement arises at partial displacement; where many mobile machines spend a considerable amount of operating time.

Inferred from the above pump data, digital transmission architectures will enable unprecedented shaft to shaft overall efficiencies; rivaling many power-split transmission architectures without the complexity of a parallel mechanical path. Thus, the system designer can now obtain power-split transmission efficiency and reliability with a high torque, infinitely variable transmission. From this point of view, digital hydraulic transmissions will be a major disruptive force in the off-highway transmission market.

APPLICATION EXAMPLE ‘A’

To better quantify the potential end user benefits of digital hydraulic architectures; a fuel consumption comparison of four different machine architectures is shown in Figure 13. The leftmost column representing the ubiquitous torque converter transmission, the second from the left representing a typical closed circuit hydrostatic transmission, the third column representing a diesel electric drive system, and the right most column representing a typical digital pump system architecture. The relative fuel consumption results shown in Figure 13 are from actual machine measurements driving an industry standard cycle which represents a medium duty and typical machine usage.

![Figure 13: Application Example ‘A’: Fuel Consumption](image)

The fuel consumption benefits are clear; the digital pump system has proven an almost 40% reduction in fuel consumption over the torque converter, and still more than 15% below the state-of-the-art diesel electric. It is important to note in this comparison that the duty cycle is not the most extreme; more aggressively driven duty cycles would widen the gap between these systems; increasing the already compelling benefit of the digital hydraulic solution. The component level efficiency improvements and system level control optimization equates to real fuel savings. And, in this example, the fuel savings were obtained without the benefit of energy storage devices; purely through loss reduction and control enhancements.

APPLICATION EXAMPLE ‘B’

As seen in the preceding example, digital hydraulic systems have the potential to provide best in breed fuel consumption when compared with existing architectures. But, even within the digital hydraulic framework; there are choices to be made to best match the requirements of individual machine types. A simulation study of a second application example shows this flexibility. The digital hydraulic systems 1-5 represent systems which take advantage of the system architectures outlined previously: the addition of digital motors, energy storage, etc.

![Figure 14: Application Example ‘B’: Fuel Consumption](image)

Thus, choices can be made within the scope of digital hydraulic architectures to balance the fuel consumption benefit with total installed cost, duty cycle requirements, existing machine architectures, and hybridization schemes.

DRIVE PERFORMANCE

One of the significant barriers to introducing new mobile machine architectures; especially for the propel function, is matching the drive performance to the requirements of the end user. The characteristics of which have been carefully tailored over many machine generations to suit individual machine types and brand image requirements. The operators of these machines have become very accustomed to the behavior of the transmission drive characteristics; any significant changes can cause adverse changes in productivity.

Here is another area where digital machine architectures have an advantage. Because of the very nature of their
low-level software control; the software parameters can be easily adjusted to create specific drive behavior. For instance, if a specific vehicle today uses a torque converter power shift type transmission, the digital hydraulic system designed for that vehicle can be made to naturally coast to yield a very soft drive feel. Similarly, if today a vehicle uses a closed circuit hydrostatic type drive train, the digital hydraulic system can be adjusted to yield progressively more and more aggressive drive response to mimic the original system. In this way, with careful pre-planning and cohesive development, any range of drive behavior can be tailored without the cumbersome hardware system changes typically required, and operator productivity can be preserved through an architecture change.

DEVELOPMENT APPROACH

In order to best capitalize on the benefits which are now possible with digital hydraulic system architectures; a focused, dedicated team of system experts involved as early as possible in the overall vehicle development cycle will be required. In order to best match system components into a high performing combination, this team must carefully understand the true performance and duty cycle requirements of each mobile machine. This, in the end, will yield superior value to the end users and maximizes the benefits to the vehicle designer along the way.

CONCLUSION

Digital pumps and digital motors are well poised to revolutionize the way mobile machines are designed today. This exciting technology is quickly becoming the key to eliminating system level inefficiencies, suboptimal control schemes, and space claim issues which have long been challenging mobile machine designers. Furthermore, these digital solutions present an excellent platform to respond to the impact of Tier 4 and future machine regulations.

REFERENCES


CONTACT

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ADDITIONAL SOURCES

Artemis Intelligent Power (www.artemisip.com)