DANFOSS DIGITAL DISPLACEMENT® EXCAVATOR: TEST RESULTS AND ANALYSIS

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Abstract

There is a long trend in off-highway vehicles toward higher energy efficiency and electro-hydraulic control. Digital pumps and motors are poised to become a significant enabling technology in this trend. This paper analyzes a 20-tonne tracked excavator that was equipped with digital displacement pumps and evaluated for efficiency and productivity. Previous research by Artemis Intelligent Power demonstrated improvements compared to a conventional, negative flow control excavator hydraulic system. With support from Artemis, the Danfoss Digital Displacement Excavator (DDE) is a step forward in terms of technology and commercial readiness. DDE is based on a CAT 320 next-generation excavator with completely electronic controls and advanced sensor and operator-assistance features. In before/after testing, DDE showed 15% higher productivity (in meters of trench per hour) and 13% higher efficiency (in meters per liter of fuel) for a trench digging cycle. Static pump efficiency is only part of the story; dynamic response and controllability contributed to the measured performance gains. Potential causes for variation in measurement were analyzed including operator variation, flow variation, and machine response.

Introduction

There is clear motivation for increasing the energy efficiency of fluid power systems: reducing carbon dioxide emissions, increasingly stringent government regulations on engine exhaust, fuel prices, and so on. Energy efficiency continues to be a topic of active research in academia and industry. Hydraulic excavators are a significant part of this research. There is a strong case to study excavators because their total energy use is high and their efficiency is rather low. Hydraulic excavators are the largest segment of the off-highway mobile equipment market and may be responsible for 60% of the CO_2 produced by construction machines [1]. Market research firms estimate that approximately 150 000 new excavators are produced annually in the range of 6 to 40 tonnes gross vehicle weight, and the production rate is increasing [2]. With a useful life of 10 years or more, there are likely over a million excavators in operation around the world.

Excavators are inefficient. A typical diesel-powered hydraulic excavator converts about a third of the engine's crankshaft output into useful actuator work [3, 4]. The remainder of the energy is lost as heat by inefficiencies in the hydraulic pumps and control valves. Considering fuel as the input, total energy efficiency is around 10%. More efficient hybrid excavators promised to reduce overall energy use, yet market penetration has been negligible. New battery-electric powertrains have similar challenges for customer acceptance since their cost is greater and operating time per charge may be less than comparable engine-powered machines. A new approach is needed that improves energy efficiency while addressing the real needs of excavator owners and operators. Customer needs are not globally uniform. For example, European customers may desire higher energy efficiency in order to reduce fuel consumption. On the other hand, with today's fuel prices, customers in North America may desire increased productivity, doing more work for the same fuel input.

Digital displacement is a disruptive innovation in hydraulic pump and motor design, superior to conventional technology in terms of energy efficiency and dynamic response. Digital displacement pumps (DDP) were first created at the University of Edinburgh and have been developed since 1994 by Artemis Intelligent Power [5]. Digital displacement units have been successfully demonstrated in a wide range of applications including wind power, automotive, rail, and off-highway vehicles [6]. DEXTER, a 16 tonne tracked excavator powered by DDP, is a notable example [3]. Building on the achievements of the DEXTER project, the goal of the present work is to integrate DDP into an excavator hydraulic system with fully electro-hydraulic controls. Desired outcomes include improved energy efficiency, productivity and controllability.

Literature Review

The basic system architecture of hydraulic excavators has been remarkably constant for the last 30 years. Construction excavators typically have tandem variable-displacement open-circuit pumps which provide power to actuators through open-center control valves. Pump displacement is adjusted either by negative flow control (hydromechanical feedback of pump flow rate) or positive flow control (hydromechanical feedforward of joystick commands). Wheeled excavators and compact excavators typically have a single pump with a pressure-compensated load-sensing hydraulic system. In any case, the control is mainly hydromechanical using pilot pressures from the operator's joysticks to shift spool valves.

There is a trend in off-highway vehicles toward more electronic sensing and control. Excavators are no exception. Automated features to help operators dig more accurately were introduced a few years ago as aftermarket additions and are now increasingly offered as standard equipment from the factory. In 2018, Caterpillar introduced "next generation" excavators with completely electrohydraulic control: electronic joysticks, many sensors, electronic commands to pumps and valves. It seems likely that other manufacturers will follow, considering the benefits of higher efficiency and better integration with automated features.

There are many ideas for increasing excavator energy efficiency. The most common is hybrid powertrains, typically in a parallel hybrid configuration with electric energy recovery and storage for the swing function. Kobelco introduced an electric hybrid excavator in 2007, Komatsu in 2008 and other manufacturers followed. Caterpillar introduced a hybrid excavator with hydraulic accumulator energy storage in 2012. Fuel savings up to 25% are possible with hybrid excavators [7]. However, in spite of higher efficiency and more than 10 years in production, market research firms estimate that hybrid excavators represent only about 2% of the market. It is clear that efficiency alone is not enough to gain widespread customer acceptance.

With recent advances in power electronics, electric excavators are now possible. Pon Equipment, a CAT dealer in Norway, now offers battery-powered CAT 323 excavators. Hyundai, JCB and Volvo have announced plans to produce compact electric excavators soon, and product announcements from other manufacturers will undoubtedly follow. The electrification trend highlights the need for more efficient hydraulic systems due to the cost of installed power capacity (battery, inverter, motor). Electrification without improving efficiency does little to reduce CO_2 emissions, considering the associated production processes and the fact that most of the world's electricity comes from fossil fuels [8].

Recovering kinetic energy is not the only way to improve efficiency. A more efficient way of transmitting fluid power to the actuators is also needed. Electro-hydrostatic actuation (EHA) is one concept, with a variable speed electric motor and a hydraulic pump for each actuator. EHA is well-known in aircraft hydraulics and has been considered for off-highway machines by academic researchers from 1997 [9] until today [10]. A conceptually similar concept has been demonstrated with engine-driven variable-displacement pumps [11, 12]. The STEAM hydraulic hybrid excavator developed by RWTH Aachen University is another notable contribution [13].

As previously mentioned, DEXTER was the first demonstration of applying digital displacement pumps to an excavator. Researchers at Artemis took a 16 tonne JCB JS160 tracked excavator with a negative flow control hydraulic system and replaced the tandem 80 cc swashplate type pumps with 2 x 96 cc/rev DDPs. Fuel saving up to 21% and productivity increase up to 28% were measured (though not simultaneously) by higher pump efficiency and better control of engine torque, which allowed operation at lower engine speeds [3]. DEXTER was successful as a proof of concept and continues to be a valuable testbed for developing novel system architectures with DDP. The present work seeks to build on these results, starting with a more advanced baseline machine. Danfoss purchased a 2018 next-generation CAT 320 excavator with electrohydraulic controls, which is advertised as up to 25% more fuel efficient than its predecessor. The authors' primary goal was to evaluate how much a market-leading machine could be improved with DDP in terms of productivity and fuel efficiency. The scope of the project was limited to replacing the hydraulic pumps. More significant changes to the hydraulic system architecture may be considered in future research.

System Description

Excavator Before Conversion

The original hydraulic system implemented a 130cc tandem pump with two outlet services. The pump was controlled with an electronic displacement control. The pump control receives its command from a machine electronic control module (ECM).

Both pump services entered a functionally split monoblock valve. The first service provided flow to right travel, bucket, boom (primary), and stick (secondary) functions. The second service provided flow to straight travel, left travel, swing, stick (primary), and boom (secondary) functions. A simplified schematic of this is shown in Figure 1. The boom and stick functions utilized their secondary spool only when the first spool was unable to provide enough flow to satisfy the flow requirements. Valve control was actuated electronically via the machine ECM. The valve was open-center but did not have negative flow control implemented. Instead, flow was maintained via the ECM. Additionally, the valve utilized a standby return flow from each pump to ensure heating and lubrication conditions were being maintained. In these respects, the valve block for this machine varied from a pilot controlled, negative flow open center valve typically found in an excavator application.

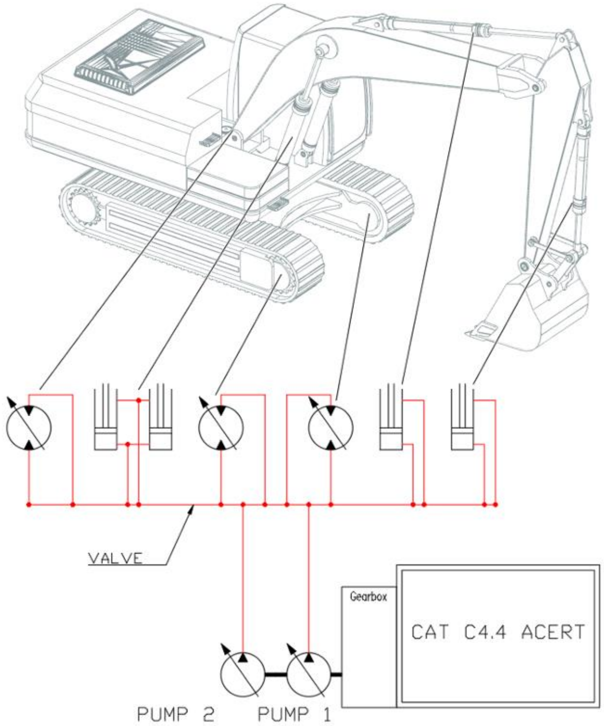

Figure 1: Simplified Valve Schematic

The CAT 320 next generation excavator implemented many operator control improvements. These included: grade assist, lower and upper threshold gating, swing gating, payload measurement, and operation assistance on swing/lift functions. Caterpillar has claimed that the implementation of these features "improves operator working efficiency by as much as 45 percent [over other grading methods] and reduces fuel consumption up to 25 percent [over previous models]" [14].

Because of the large differences in hydraulic control from older models, valve response was carefully measured to ensure the machine felt the same to an operator. Despite this desire for the machine to feel the same, the electronic valve operation allowed for much more precise control of the hydraulic system. An example of an excavator of this type is shown in Figure 2.

Figure 2: Danfoss Digital Displacement Excavator

Because of the implementation of all the new features on the "next generation" CAT 320 excavator, the swashplate pump is acting with the slowest dynamic response in the hydraulic system. This supports the hypothesis that the machine should actuate with less delay once the DDP was installed. This was driven by the change to the electrohydraulic pump controls.

Excavator After Conversion

When the DDP was installed, a 1.5 speed increase gearbox with a submerged gear was required to maintain system flow. The DDP was a 96cc tandem unit. At the 1650 rpm typical engine operating speed, the DDP's maximum flow rate was nominally 475 L/min. Due to sizing differences, after conversion the DDP produced 10 percent more flow than the original pump (429 L/min). To operate the DDP, two microcontrollers were added to the system to actuate the pumps. Additionally, a Danfoss PLUS +1 microcontroller was added to the machine to allow for easy interfacing between the DDP controllers and the CAT ECM modules. An image of the DDP pumps and gearbox is shown in Figure 3. These were the only changes made to the excavator.

DDP Characteristics

Digital displacement pumps are based on a radial piston pump design. Variable flow rate is achieved by controlling the output of each piston with high-speed on/off valves. Because the pump only pressurizes the minimum number of pistons needed to provide the required displacement volume, DDP has lower power losses and higher efficiency than conventional axial piston pumps (see *Figure 4*).

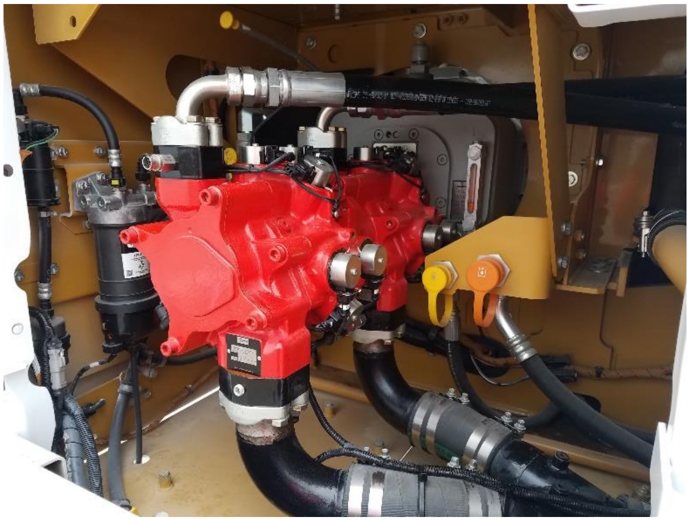

Figure 3: DDP and Gearbox

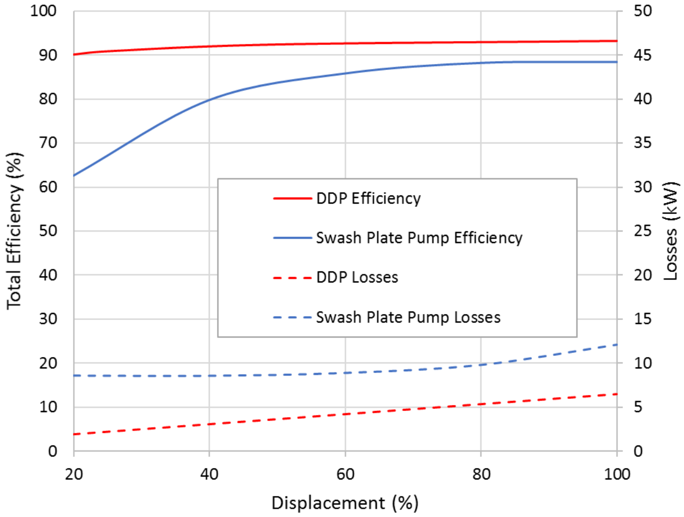

Figure 4: Pump efficiency and power losses

DDP dynamic response is faster than conventional technology. The time required to change displacement from zero to 100% (or from 100% to zero) is equal to half of one shaft rotation. Signal delay associated with controller processing and valve response is about 5 ms. Therefore, at 1500 rpm, pump response time is 25 ms or less with no overshoot or settling time.

To be fair, digital displacement also has some disadvantages. The cost of the pump and controller is higher than a comparable swash-plate pump. Due to the digital flow control, flow ripple amplitude is larger than conventional pumps, particularly at displacement fractions < 25%.

Experimental Method

Trenching

Trenching has historically been the most common operation of an excavator. This operation uniquely evaluated every function of an excavator including: boom, stick, bucket, unloaded swing, loaded swing (for backfilling), and travel functions. It also evaluated fine operation control which is required to maintain a consistent trench depth. This was the truest test of an excavator's general use capabilities. Unfortunately, this test came with tradeoffs in testing applications because the density of the soil being excavated varied through the test. As a result, there was more variability in the data than there would be for a test performed on the same date with the same soil and humidity. These soil density and humidity differences also affect the soil breakout force, but these should be comparable, as testing was performed at the same test facility utilizing the same soil both before and after conversion, with similar meteorological conditions.

For this test, the length of the trench before and after conversion was evaluated by direct measurement. Trenches were held to 5 ft [1.52 m] wide (one bucket width after excavation) by 8 ft [2.44 m] deep. The operator needed to both dig and fill a trench in one hour for each mode of operation. All other testing conditions were held constant before and after conversion. The goal of the test was to trench and fill as far as possible in the designated time with the machine. Because of the potential for high variation in the results based on operator expertise, an external, expert operator was utilized for this testing. The same operator was required for testing both before and after conversion.

Mass Excavation

Another common use for an excavator is to perform a mass excavation of materials. This test evaluated almost all the same functions of an excavator as the trenching test (except for loaded swing and travel functions) while providing much more rigorous constraints on testing conditions. When performing the test, soil that has already been dug three times was loaded into dump trucks that were weighed before returning the soil to the excavation site concurrently over one hour intervals for several different operation modes. Reuse of this soil ensured consistent density over the evaluation period. It also ensured that the breakout force required to free the soil from the ground was minimized. Removing these variations provides a more reliable result when evaluating productivity and calculated efficiency of the excavator. As with the trenching test there is the potential for high test variation based on the expertise of the operator, so an expert operator was utilized. All other test conditions were held constant. For both the trenching and mass excavation test the operational theory was to collect a relatively small amount of data in a highly controlled test to get reliable, robust information with limited time and financial resources.

Ideally, collecting a large amount of test data over a much longer period with the same testing constraints would have been preferred. This larger body data would be subject to stronger statistical evaluation but would also require a larger time and financial commitment than was feasible. Additional field testing is planned as future work. When evaluating the data collected, there was no trend of improvement or deterioration of operator capability at executing the test.

Individual Cylinder Behavior Characterization

When considering the benefit of a DDP in an electronic displacement control system, one potential benefit is the reduced response time between a command sent to the pump and the machine responding to that command. Until this time, it was assumed that the DDP would be able to actuate a cylinder faster, but that this increased response would have a negligible effect on the overall machine productivity. After a discrepancy between calculated pump efficiency and machine fuel efficiency was uncovered this was evaluated more in depth. To evaluate the cylinder thoroughly this portion of testing was broken into three distinct parts that are interrelated.

Cylinder Response

Cylinder response testing looks at the time between when a step command is issued from the joystick to when the cylinder begins actuation. The response time in humans has been recorded at 150 ms, but the lower threshold for perception of a delay can be as low as 75 ms [15]. As a result, a hydraulic system with a reduced response time will have less latency to an operator and will allow for an easier human-machine interaction. This reduced time to respond may also influence the total time of actuation for a cylinder.

For this test a step input was provided to a cylinder from a joystick and the time between the input and physical cylinder actuation is recorded.

Cylinder Steady State Time

If total flow to a cylinder is reaching steady state faster in a cylinder, then the actuator should be accelerating at a higher rate than before conversion. If the digital pump caused a cylinder to reach steady state actuation faster, it would be logical to assume the machine will operate faster overall. Additionally, if the cylinders were reaching steady state faster after conversion there would be less transient time in the excavator where loading conditions are less predictable.

Cylinders were actuated with a step function via joystick and the command was held until the cylinder reached the end stop. The position data from this actuation was recorded. This data was then differentiated to calculate the instantaneous velocity of the cylinder. After the derivative was calculated, the velocity profile for each run was averaged to ensure a representative curve. An important detail in this analysis is that the data only looks at the velocity profile from the time the cylinder begins actuating. This means that the cylinder response time is not included in testing result.

Cylinder Cycle Time

After evaluating the time it took the cylinder to reach steady state, the cycle time for a single cylinder actuation from end stop to end stop (except for the boom which not able to fully retract due to the ground position) was analyzed. This test was performed by inputting a step command to the joystick and recording how long it took for the cylinder to fully stroke.

Experimental Results

Trench Testing

After converting the machine to a DDP solution the excavator was able to trench 15.3% further in an hour as shown in Table 1. These results also indicate that a larger amount of fuel was consumed in the allotted testing time. However, when evaluating the calculated efficiency as a function of distance traveled per unit fuel consumed it becomes obvious that the DDP solution provides a much more efficient application.

Table 1: Trenching Results

Mode	Meters/Hour	Liters/Hour	Meters/Liter
Baseline	51.9	21.8	2.38
Converted	59.9	22.1	2.70
Delta [%]	15.3	1.7	13.4

Mass Excavation Testing

Results for the mass excavation test were evaluated differently than those of the trenching test because of the minimized soil density variation. For the mass excavation, instead of looking at distance trenched, the overall weight of soil excavated was evaluated. Evaluating the results this way allows for a direct measurement of work done by the machine in a predetermined amount of time.

Table 2: Mass Excavation Results

Mode	Tonnes/Hour	Liters/Hour	Tonnes/Liter
Baseline	341.6	20.6	16.6
Converted	398.7	22.4	17.8
Delta [%]	16.7	8.6	7.5

Based on the results in Table 2 the machine after conversion was able to excavate more soil at the cost of an increase in fuel consumed. Due to reduced losses in the overall machine a greater weight of soil was moved per unit fuel.

Cylinder Response Time

The cylinder response time are shown in Table 3 based on the results of experimental testing before and after conversion.

Table 3: Machine Response Times

Function	Direction	Average Response Before Conversion [ms]	Average Response After Conversion [ms]	Delta [%]
Boom	Extend	172	120	-30.1
	Retract	366	251	-31.4
Stick	Extend	189	174	-7.9
	Retract	255	186	-27.3
Bucket	Extend	165	164	-0.7
	Retract	176	143	-18.3

From these results the DDP decreases response time relative to a swashplate style pump.

Cylinder Steady State Time

From the test methodology outlined a velocity vs time plot was generated. Figure 5 shows this profile.

It is valuable to note that the velocity profile shown is for the bucket cylinder extension. This function showed the least change in cylinder cycle time in Table 4 possibly because there is a large mass attached to the cylinder that acts with gravity as it actuates.

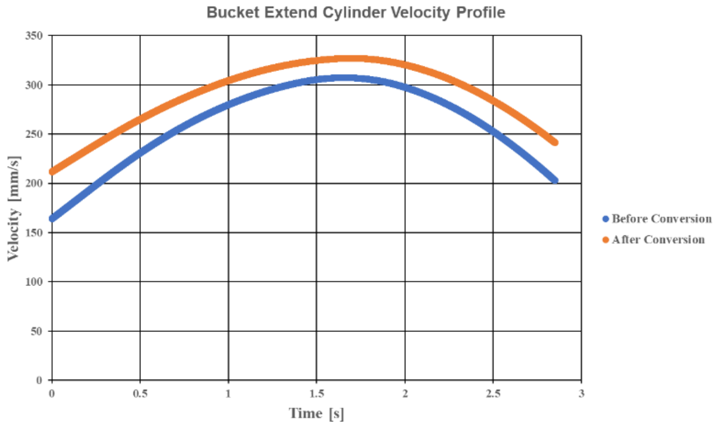

Figure 5: Cylinder Velocity Profile

Cylinder Cycle Time

The results of cylinder cycle time are displayed in Table 4. The results of experimental testing before and after conversion are shown in the table. It is important to note that all values shown below are averaged values over a minimum of three test runs. This minimizes error in any individual measurement.

Table 4: Single Function Cycle Times

Function	Direction	Cycle Time Before Conversion [s]	Cycle Time After Conversion [s]	Delta [%]
Boom (Partial)	Extend	3.0	2.5	-14.5
	Retract	2.2	1.9	-13.6
Stick	Extend	3.2	2.7	-12.7
	Retract	2.9	2.6	-6.3
Bucket	Extend	3.8	3.4	-7.9
	Retract	2.1	1.9	-5.0

Analysis

Direct Flow Comparisons

In the system description section, the authors mentioned that converting the machine to a digital pump required the use of a gearbox with a 1.5 increase ratio. This led to a 10 percent increase in usable flow for the system. This difference in flow was evaluated to determine if it could adequately account for the increase in both productivity and calculated efficiency of the system.

To evaluate the effect this difference in flow had on the system, both the trench test and productivity test were run with the DDP limited to 90% displacement—the same flow capacity as the baseline pump. These results were then compared to both of the other test conditions (the baseline machine and the machine after conversion with the increased flow).

Table 5: Trenching Flow Matching Comparisons

Mode	**Meters/Hour**	**Liters/Hour**	**Meters/Liter**
Baseline	51.9	21.8	2.38
Matched Flow	57.6	22.8	2.53
Increased Flow	59.9	22.1	2.70
Matched Flow vs Baseline Delta [%]	11.2	0.6	10.5
Increased Flow vs Baseline Delta [%]	15.3	1.7	13.4

The results from the mass excavation test are show in Table 6. These results also indicate an increase in productivity, but at a cost to fuel consumption. As a result, the volume of soil per liter of fuel decreases when pump flow capacity is increased 10 percent.

Table 6: Mass Excavation Flow Matching Comparisons

Mode	**Tonnes/Hour**	**Liters/Hour**	**Tonnes/Liter**
Baseline	341.6	20.6	16.6
Matched Flow	388.7	21.6	18.0
Increased Flow	398.7	22.4	17.8
Matched Flow Delta [%]	13.8	4.4	9.0
Increased Flow Delta [%]	16.7	8.6	7.5

Operator Control Changes

Another possible cause for improved machine performance after converting to the DDP was machine operator variation. If the machine was outputting different power, perhaps the operator would request different commands from the joystick. Since the operator was an expert at machine usage, not a professional machine tester they would be prone to "correcting" operation to perform the most productive dig cycle possible. If there was a significant change in the dig cycle operation it may affect the productivity and fuel consumption rate for the machine over time. To address this concern, a histogram of each joystick command was compared for each test. The results shown in Figure 6: Operator Commands Histogram is a representative sample of these commands for a joystick function. The upper chart is for a trenching operation where flow is matched to the baseline pump. The lower chart is the same trenching operation where maximum hydraulic flow was increased by 10 percent. The charts are nearly identical, indicating that the operator's commands were essentially the same in both conditions. This held true for testing before and after installation of the DDP as well.

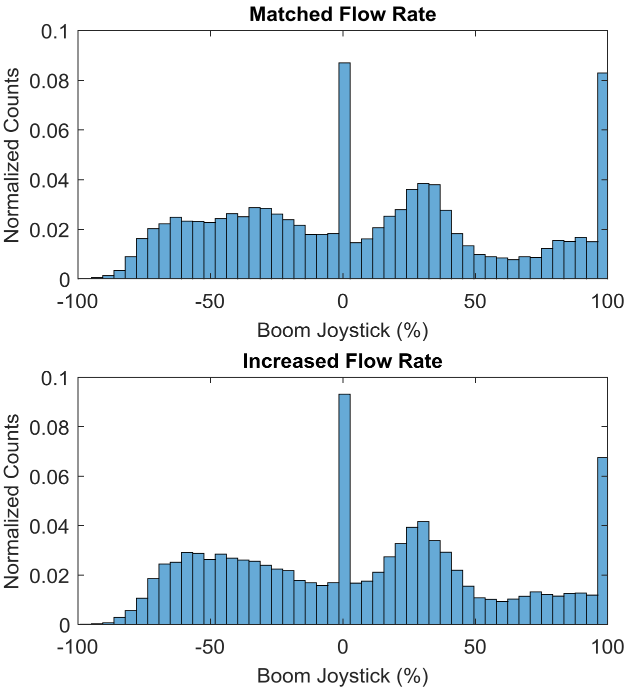

Figure 6: Operator Commands Histogram

Energy and Calculated Efficiency

Energy results for the trenching and excavation tests are shown in Table 7. Average power was calculated by integrating instantaneous power with respect to time and then dividing by the time duration. Engine power output was determined by the engine's speed and torque, reported on the J1939 CAN bus by the engine ECM. Pump output power was calculated directly from measured pressures and flow rates at the pump outlets. Pump input power was then calculated with steady-state maps based on the measured speed, pressure, flow rate and temperature of each pump. Total pump efficiency is the calculated ratio of total pump output power to total pump input power. Actuator power was calculated from cylinder and motor pressures and the time derivative of measured positions.

Positive output power refers to work done by the actuators on a resistive load, such as lifting the boom. Negative actuator power is work done by gravity or inertia on the actuators, such as lowering the boom or decelerating the swing drive. Only the positive work is counted in Table 7.

Table 7: Digging Tests Energy Analysis

		Average Power in kW				Average Power Delta Compared to Pre-conversion Test				
Test Configuration	**Operation**	**Engine Output**	**Pumps Input**	**Pumps Output**	**Actuators Positive Output**	**Engine Output**	**Pumps Input**	**Pumps Output**	**Actuators Positive Output**	**Pumps Total Efficiency**
Pre-conversion	Mass Excavation	87.3	77.7	66.7	30.2					0.859
Post-conversion matched flow	Mass Excavation	93.4	85.3	77.6	36.2	7.0%	9.9%	16.3%	19.7%	0.909
Post-conversion +10% flow	Mass Excavation	93.4	86.2	78.4	37.0	7.0%	11.0%	17.5%	22.4%	0.910
Pre-conversion	Trenching & Filling	92.8	84.6	72.4	34.7					0.855
Post-conversion matched flow	Trenching & Filling	94.0	87.5	79.6	37.0	1.3%	3.4%	10.0%	6.7%	0.910
Post-conversion +10% flow	Trenching & Filling	94.2	88.3	80.5	36.7	1.5%	4.4%	11.2%	5.8%	0.911

Discussion of Results

Mass Excavation. From Table 7, pump efficiency was calculated to be about 6% higher with DDP compared to the pre-conversion baseline. At the same time, pump output power increased by up to 17.5%. From Table 6, excavator productivity in tonnes/hour increased up to 16.7% and excavator fuel efficiency in tonnes/liter increased up to 9%.

Trenching. Similarly, calculated pump efficiency with DDP was about 6% higher than the baseline test. Pump output power increased up to 11.2% (see Table 7), excavator productivity in meters/hour increased up to 15.3% and excavator fuel efficiency in meters/liter increased up to 13.4% (see Table 5). Clearly, these results cannot be explained only by the change in pump steady-state efficiency.

Cylinder Response Testing. While the data is noisy, there does seem to be a decrease in response time after the DDP was installed on the machine. This response time seems to also be affected by the mass acting on the system. For functions that act with gravity there seems to be less of an effect on the response time than for those that actuate against gravity.

Cylinder Steady State Time. It is clear from Figure 3 that the cylinder is accelerating at a faster rate with the DDP than before conversion. This would indicate that machine is reaching steady state faster. This longer time at steady state should also be reflected in an increase in productivity or trenching length.

Cylinder Cycle Time. As Table 4 indicates there was a significant decrease in cylinder cycle time after converting to the digital pump. This result varies from function to function and may be limited in the ECM software or may bear some relationship to the mass for a function acting in the same direction as gravity. Since there was no access to this software this remains an unproven hypothesis. However, the time decrease in each of these functions should carry over to the trenching and excavation results as a distance increase and a volume increase respectively. This is borne out in the results we are seeing from the trenching and mass excavation testing results.

Direct Flow Comparisons. When evaluating the results of the trench testing in Table 5: Trenching Flow Matching Comparisons it becomes clear that there is some added distance and fuel consumption benefit to the increased in pump output flow. This benefit seems to be about two percent, which is still not enough of a change to account for the discrepancy between calculated pump efficiency and calculated machine fuel efficiency. To verify this two percent increase, a flow comparison test was also performed for the mass excavation test.

Based on the histogram results in Figure 4, the operator's commands were essentially the same with or without the extra 10% in maximum flow rate compared to the baseline.

Pump efficiency and dynamic response contribute to productivity. The goal of the project was to increase the excavator's productivity with digital displacement pumps. The measured results indicate that productivity gains were not due to increased pump efficiency alone. DDP dynamic response and controllability also contributed. The operator was able to take advantage of the more responsive hydraulic system to increase engine power, actuator power and soil moved. Because of the interactions between static and dynamic characteristics, it is difficult to separate the incremental benefits of efficiency and response. The main point is that there is indeed an interaction, and the hydraulic system's efficiency characteristics cannot be understood only in terms of static metrics.

Conclusions

On a 20 tonne, next generation, CAT excavator, a digital displacement pump was installed in place of the swashplate pump with the goal of improving machine productivity. After conversion a 15 to 16 percent improvement in productive work over time was observed. At the same time, an increase of 7.4 to 13.4 percent improvement of work per unit fuel was also observed. When an analysis of measured data was complete it indicated a 6 percent increase in average pump efficiency but a 10 to 17.5 percent increase in pump output power.

An investigation was implemented to understand the differences between the expected and observed values from the analysis. Through this analysis it was determined that a 10 percent increase in maximum flow only accounted for a 2.5 percent increase in productivity. Furthermore, it was determined that controllability of the machine was maintained, and that the machine operator did not alter his excavation methods based on the maximum pump flow. When evaluating individual cylinders there was a 19.2 percent average reduction in response time to functions, a 10.9 percent average increase in cylinder velocity, and a 10.5 percent decrease in cylinder cycle times.

While previous research had shown that the DDP has a higher total efficiency and faster dynamic response rate, this had not previously been considered a major contribution to overall machine performance. As a result, static efficiency maps had largely been used to evaluate the benefit of using a DDP.

To summarize, the 15-16% increase in productivity comes largely from a combination of the faster response, faster time to steady state, faster individual cylinder cycle time, and DDP efficiency. Further analysis would be required to work out how these factors combine to give the final result.

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