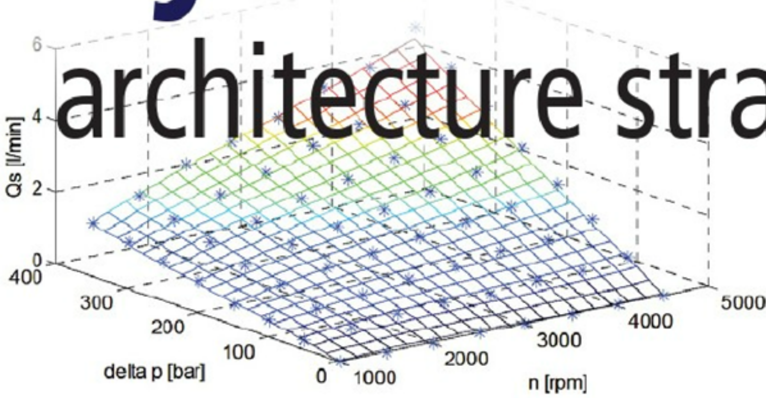
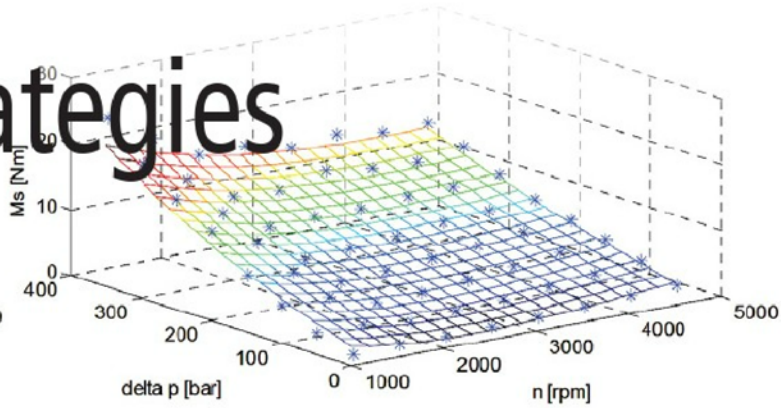
Hydraulic architecture strategies



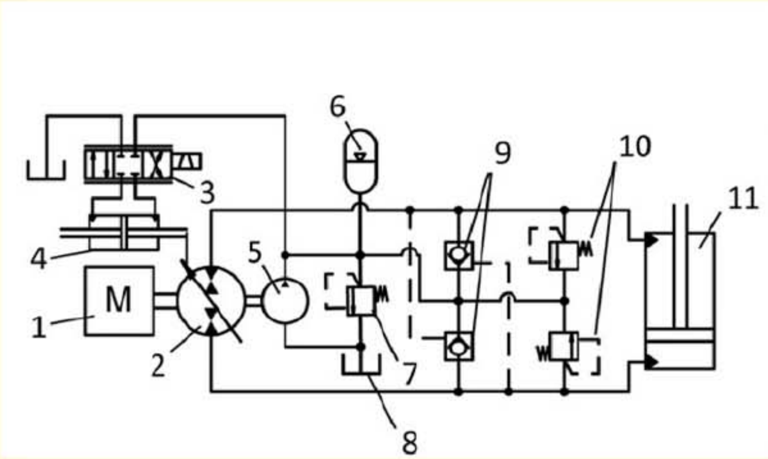


Researchers compare two different rule-based power-management strategies, in terms of their resultant fuel consumptions, through a simulation study as applied to a hybrid hydraulic multi-actuator displacement controlled system.

In recent years there has been a thrust toward improving the fuel and energy efficiencies of both passenger vehicles and off-highway equipment, driven by rising fuel costs and stricter emissions laws.

Research into these systems has involved operation of the energy source (engine) at more efficient operation points through power management, as well as transmission mechanisms for recovery and capture of energy. Electric hybrids that use batteries and capacitors for energy capture and storage, as well as hydraulic hybrid mobile machines that use accumulators for energy storage, have been studied toward this end.

A power-management strategy is a supervisory-level control system that regulates energy conversion, storage, and transmission while achieving the desired system operation. For a hydraulic excavator, "desired system operation" im-

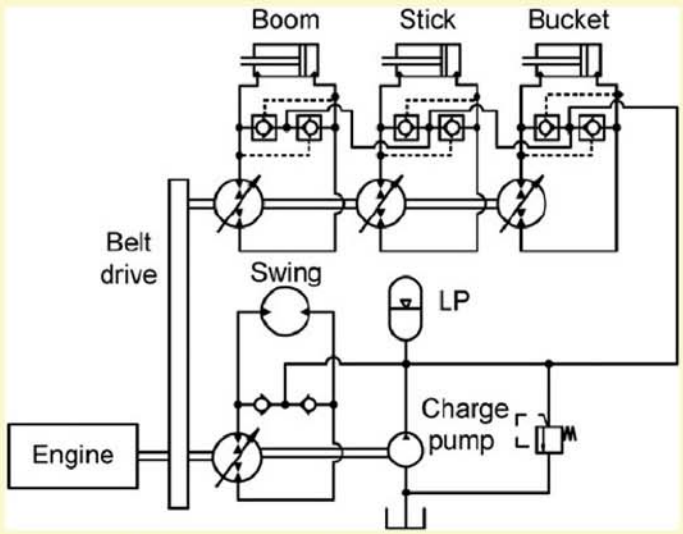


1. Power source (engine)	
2. DC pump/motor	
3. Pump control valve	
4. Pump control cylinder	
5. Charge pump	
6. Accumulator	
7. Charge pressure relief valve	
8. Reservoir	
9. Pilot operated check valves	
10. High pressure relief valves	
11. Hydraulic cylinder	

Schematic of a single displacement controlled (DC) actuator circuit, which tends to have fewer losses due to the absence of control valves between pumps and actuators.

plies satisfying the flow and power requirements of a given duty cycle while minimizing fuel consumption during the cycle. The power-management strategy would adjust engine speed and pump displacements toward meeting these goals.

Researchers from **Purdue University** aimed to investigate the possibility of further fuel savings through advanced power-management strategies for a hybrid displacement controlled (DC) excavator system. The parallel system architecture is used, wherein an extra storage pump is added to transfer power to and from the accumulator to the engine shaft.

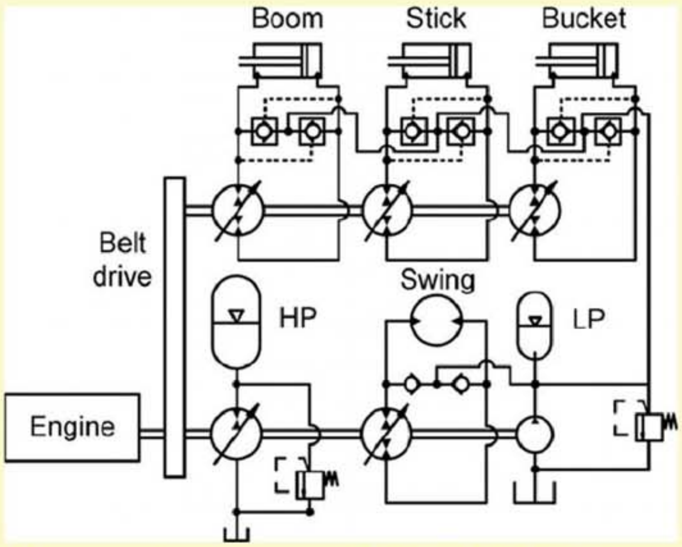


Simplified schematic for an excavator with DC actuation. Only the primary digging functions are shown, and the auxiliary functions share pumps with the primary digging functions.

Displacement-controlled actuation

DC-actuated circuits use variable displacement pumps and do not rely on throttling of flow between pump and actuator. In multi-actuator circuits, there is one pump supplying each actuator. For linear actuators with single-rod cylinders, pilot-operated check valves are required to account for the difference in areas on either side of the piston.

A low-pressure supply (usually referred to as charge pump) can be used to sup-



Schematic of a parallel hybrid DC excavator. An extra pump/motor was added on the engine shaft to transfer energy to and from the high-pressure accumulator.

ply the required balance of flow through the above check valves, and also to power the pump control system. Additionally, a low-pressure accumulator is also used as a flow source to reduce fluctuations in the low-pressure line. The low-pressure accumulator is not a means of energy storage.

It should be noted that the prime reason why DC circuits have fewer losses is the absence of control valves between pumps and actuators. There are no throttling losses. The DC circuit also inherently facilitates energy recovery from the actuators, e.g. when gravity aids lowering of the actuator (boom or stick), or when an actuator is coming to rest from a large speed (e.g. the swing).

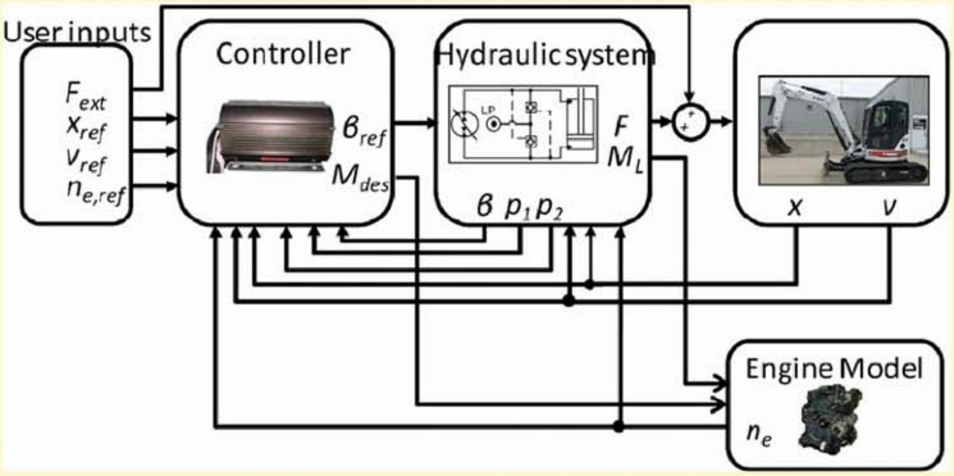
Sizing hybrids

An obvious means of going from the non-hybrid DC system to a hybrid DC system with energy storage capability is to add an extra pump/motor on the engine shaft (or "storage unit"), to transfer energy to and from the high-pressure accumulator.

Energy recovered from any of the actuators can be put back onto the engine shaft, just as in a non-hybrid. To charge the accumulator, the storage unit is operated in pumping mode, while to discharge the accumulator, it is operated in motoring mode. Such an architecture is referred to as the parallel hybrid architecture.

A fast, aggressive digging cycle, representing an upper bound on total power demanded from the hydraulic system, was chosen for this study. Peak engine power was reduced by 50% while providing for higher power requirements through use of the accumulator. The cycle simulated here did not involve use of the travel.

Thus for sizing, it should be ensured that the accumulator captures at least all the balance energy whenever the power requirement is below target power in a



The simulated system involved modeling of the system hydraulics, system mechanics (including the kinematics and dynamics), engine dynamics, and the controller. The model was developed in Matlab Simulink/SimMechanics.

cycle and releases this energy whenever the power requirement goes above the engine peak power. The accumulator was thus sized to provide all the energy required above the target engine power.

The storage unit on the other hand needed to be sized to provide enough flow to charge (or discharge) the accumulator (assuming a speed of 2500 rpm) so that the balance of power at the engine was made up for.

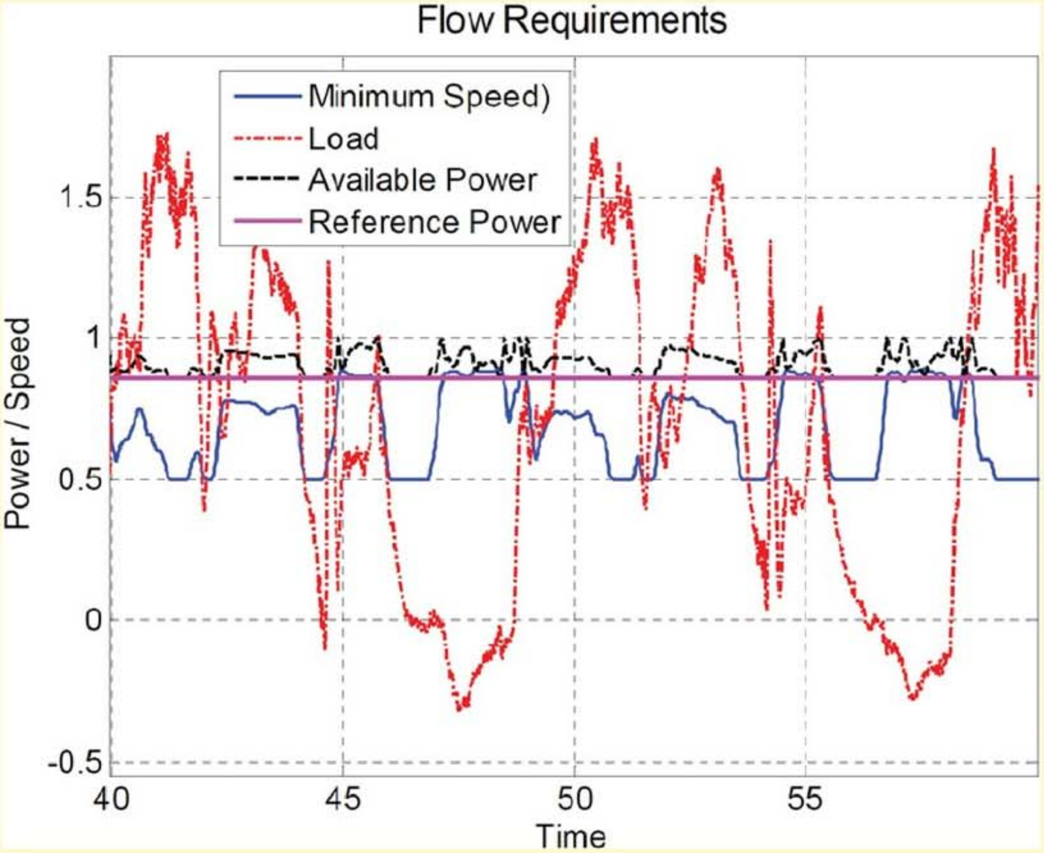
Simulation model

System simulation involved modeling of the system hydraulics, system mechanics (including the kinematics and dynamics), and engine dynamics, as well as the controller. The model was developed in Matlab Simulink/SimMechanics.

The pump is the main source of power loss in a DC actuator, and thus an accurate pump model is essential. Steady-state torque and volumetric losses were measured according to ISO 4409 across the range of operating pressures, speeds, and displacements for an 18 cc/rev pump (which has been installed in the prototype machine).

Pump controllers (included in hydraulic system model) ensure that the actual swash plate angles follow the commanded swash plate angles. The pump adjustment systems are essentially comprised of servo-valves that are commanded to go to certain positions depending on the swash plate angle error.

A brake specific fuel consumption map of the full-size engine was generated using measurements made under various conditions by **Analytical Engineering** Inc., while the engine was disconnected from the excavator system. The fuel map is essential to compute fuel consumption of an engine. The dynamics of the



A brake specific fuel consumption map of the full-size engine was generated using measurements made under various conditions, while the engine was disconnected from the excavator system.

engine were assumed to be first order, and the maximum output torque of the engine was limited as a function of engine speed based on the maximum torque curve of the engine.

Since the goal was to investigate further fuel savings with a downsized engine, a fuel map for an engine of half the nominal power was also important. As this information was not available, the maximum torque curve of the full-size engine was scaled by 50%, assuming that the speed range and fuel efficiency contours of the smaller engine were identical to that of the larger engine.

Power-management strategies

Any power-management strategy for a non-hybrid DC excavator would have to deal with five degrees of freedom. In the case of a parallel hybrid excavator, there is an extra degree of freedom due to the storage pump.

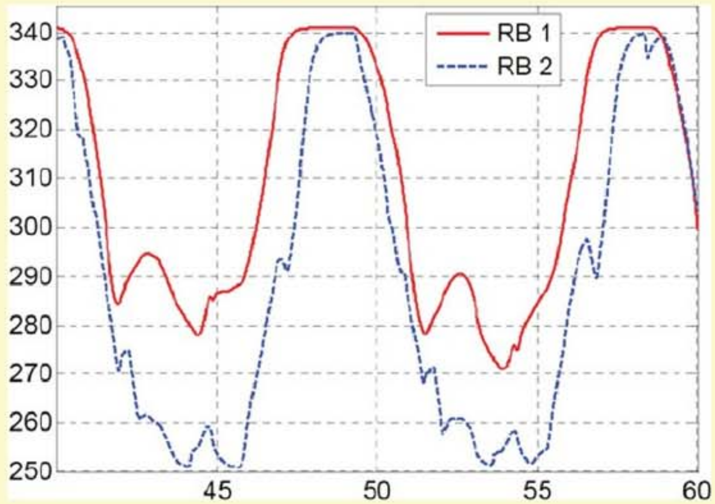
However, if a duty cycle can be characterized in terms of requirements on actuator velocity and loads at every instant of time, those requirements can be translated to flow and torque requirements on each of the pumps driving the actuators. As a result, the required displacements on those pumps can be derived in terms of the engine speed.

For a Rule-Base 1 strategy, it was desired to keep the engine operating at maximum speed for every instant of time.

If the accumulator is empty, the storage pump torque is simply set to the difference between the reference engine torque and load torque. If the load torque is lower than reference torque, the storage pump charges the accumulator by using the balance torque from the engine. If the load torque is higher than the reference torque and charge is available, then the storage pump is motored to provide the balance torque.

The power management also sets limits on the storage unit's swash plate angles during charging and discharging. If accumulator pressure is close to relief pressure, then the swash plate command is limited to 10% of maximum swash plate angle to avoid flow over relief. Conversely, if the pressure is close to minimum system pressure, the swash plate angle is constrained to be greater than -5% of maximum swash plate angle, to avoid discharging the accumulator too much.

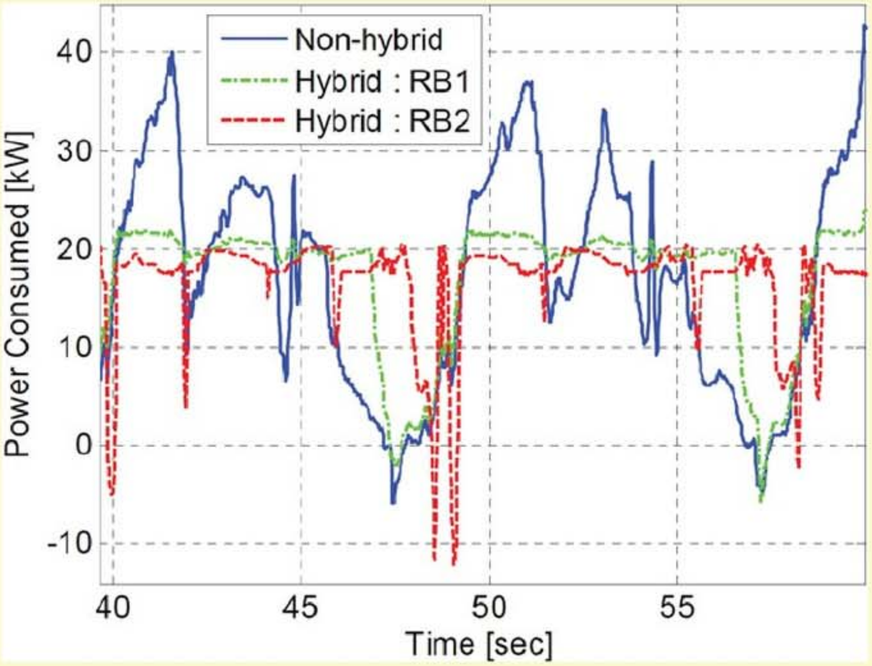
For a Rule-Base 2 strategy, it was desired to maintain the engine and pumps in high-efficiency regions while meeting



A comparison of the accumulator pressures. The accumulator spent more time fully charged for the less-demanding Rule-Base 1, while due to the acceleration (and deceleration) requirements of Rule-Base 2, the accumulator spent less time fully charged, and more time charging and discharging.

cycle requirements (flow and power) at every instant of time. Swash-plate type pumps are more efficient at lower speeds and higher displacements, and the excavator diesel engine is also more fuel efficient at low speeds and at higher torques.

Thus, the controller commands minimum engine speed and tries to operate at a constant, high power. Note that the required load power on the engine is calculated from the torque required to accelerate the engine (and pumps) and



It is clear that going from the DC non-hybrid to the parallel hybrids can allow reduction of peak engine power by 50%. Engine operation was also more steady and efficient in the hybrid.

the sum of the torques from the pumps running the actuators.

The minimum engine speeds required for each pump to supply the desired flow assuming 100% pump displacements were calculated, and the maximum of these were chosen to calculate the minimum allowable engine speed. If speed was found to be less than 2000 rpm, it was reset to 2000 rpm. The reference engine power can only be met at speeds higher than 2000 rpm.

Next, the maximum power available was calculated using the speed-power map—if it was found that the maximum power available at minimum was lower than the pre-calculated total power requirement of the cycle, the speed was increased (by searching the speed-power map) until the desired power was available. Due to the correction in the previous step, however, this correction was typically not required.

Since engine speed is always set to pre-calculated minimum desired speed, the rules only need to account for control of storage unit displacement.

If the accumulator is empty and there is a resistive load on the engine, then balance power (if any) from the engine is used to charge the accumulator.

With a partially charged accumulator and a low resistive load, the accumulator was charged using the balance engine power. With a partially charged accumulator and a high resistive load, it is necessary to discharge the accumulator to supply the balance power, while operating the engine at reference power.

For an aiding load, and an accumulator that is partially charged, it is necessary to keep operating the engine at commanded power and charging the accumulator. Set displacement of storage pump to 0%, if the accumulator is full.

It should be noted that the aggressive cycle simulated here has very few instants where there is an aiding load on the engine. Additionally, a lower bound is placed on the commanded storage unit swash plate angle when the accumulator is nearly empty, and an upper bound placed when the accumulator is nearly full.

Getting results

For Rule-Base 1, the engine operated mostly at high speeds. However, the engine operation was mostly at peak power, which fell in its most fuel efficient zone. Also, engine speeds stayed high throughout the cycle, although lower than the speeds for a non-hybrid.

For Rule-Base 2, the tracking performance of the hybrid was also compared to that of a DC non-hybrid. It was clear that this system tracked reasonably well, except for the boom. This was much the same as the performance of the Rule-Base 1.

The commanded engine speeds were generally followed, except at instances in time where the torque required by the actuators was higher than the maximum engine torque, and there was not enough charge available in the accumulator for accelerating the engine.

The fuel consumption of the engine was plotted over the engine fuel map. Operation was concentrated near the reference power (17.8 kW). Whenever the power required was more than the reference power (this could be either due to acceleration requirements, or simply flow requirements), the point of operation is above the reference power line, and generally at the wide-open

	DC Non-Hybrid	Hybrid Rule-Base 1	Hybrid Rule-Base 2
Fuel Consumed (g)	208.4	168.5	163.3
% Improvement	(Baseline)	19.16%	21.64%
Energy Required (kJ)	2149.2	2174.3	2144.7
% Improvement	(Baseline)	-1.6%	-0.2%

Energy and fuel comparisons of the three systems under consideration, with the non-hybrid DC system serving as baseline.

throttle curve. Several points of operation were dispersed substantially below the reference power line as well, which showed the success of the strategy in limiting the engine power (and thus fuel consumption).

The storage pump displacements mostly stayed high in magnitude while charging or discharging. When the accumulator was close to being full or empty, pump displacements were limited.

The accumulator spent more time fully charged as a consequence of the less-demanding Rule-Base 1, while due to the acceleration (and deceleration) requirements of Rule-Base 2, the accumulator spent less time fully charged and more time charging and discharging.

It was expected for the parallel hybrid that there would be an increase in overall energy requirements but a reduction in fuel consumption due to the addition of an extra unit (storage unit) on the engine shaft and operation in more efficient areas of the engine fuel map. Also, the minimum system pressure setting of 250 bar (3625 psi) implied that the storage unit was operated at high pressure, thus increasing standby losses.

While the first strategy commanded the engine to operate at maximum speed and constant torque, the second strategy commanded the engine to operate at minimum required speeds to meet flow requirements and the pumps at high displacements. The second strategy thus attempted to exploit both degrees of freedom available, i.e. engine speed and storage pump displacement, for reducing fuel consumption, while the first one exploited only one degree of freedom.

Both strategies showed significant fuel savings over a DC non-hybrid system, but the relative improvement for the second rule-base over the first one is not very large for the simulated cycle. This was because of the high power and flow requirements of the cycle, due to which the engine was always operating either at high power or at high speeds.

The difference in fuel savings for the two strategies would be more apparent for a less aggressive cycle, such as pipe-laying or a novice digging cycle, which will be investigated in the future. Additionally, use of a shut-off valve, to reduce the high idling losses of the storage unit, would also be investigated in the future.

This article is based on SAE technical paper 2011-01-2273 by Rohit Hippalgaonkar and Joshua Zimmerman, Purdue University, and Monika Ivantysynova, Purdue University-West Lafayette.

Kobelco's new excavator makes the mark with intelligent hydraulics

The Kobelco SK210 Mark 9 features an operating weight of 47,840 lb (21,700 kg) and a dig depth of 21.23 ft (6.47 m). The new model delivers 160 hp (119 kW).

Kobelco Construction Machinery America's full-size SK210 is now part of the company's Mark 9 series, which includes Tier 4 models such as the SK260, SK295, SK350, and SK485 excavators.

Featuring an upgrade to Kobelco's intelligent hydraulics and a new Economy power mode, the SK210 Mark 9 is equipped with what Kobelco claims is "the industry's first" selective catalytic reduction (SCR) emissions solution that allows excavators to meet Tier 4 Interim regulations. SCR is an aftertreatment-only solution that allows the excavator's engine to optimally generate power.

The high efficiency in the combustion process significantly reduces fuel consumption while improving power. SCR with diesel exhaust fluid (DEF) is also the preferred choice for working in extreme temperatures.

"The average rate of consumption of

DEF is about 5% of fuel, so refilling is only required every fourth or fifth fuel-tank refill—or, on average, every eight to 10 days," said Reece Norwood, Kobelco Platform Manager.

The upgrade to electronic control of the common rail fuel injection on the SK210 Mark 9 excavator gains efficiency, while also providing more exact fuel metering and fuel/air ratio.

For improved system efficiency and reduced component wear, the SK210 Mark 9 also features a fully automatic engine and hydraulic warm-up system. This warms the hydraulic circuit to an optimum 126°F (52°C).

A new ROPS/FOPS-certified cab provides a more comfortable work environment, and a low engine cover improves operator visibility and productivity. The larger, isolation-mounted cab on the SK210 Mark 9 excavator accommodates all operator sizes, says Kobelco. Repositioned controls, moveable front and door windows, and more glass improve visibility from the sides of the cab.

A new control monitor provides key operating data—including a new function that graphs fuel consumption per hour—and a rear camera view to expand the operator's view to the back of the machine. An optional air-suspension seat with heated cushions provides additional operator comfort.

To match work operations, the work mode system provides three modes. H Mode, for heavy-duty excavation and loading work, gives priority to the workload at high speed. S Mode, for standard digging and loading work, provides versatility. E Mode, for economy, leverages more of the intelligent hydraulics features to deliver exceptional fuel efficiency with productivity for normal digging conditions.

There are also two attachment modes—B Mode, breaker/hammer optimized (one-way hydraulic flow) and A Mode, for auxiliary attachment work such as demolition with a crusher/nibbler breaker or shear (two-way/two-pump flow).

An upgraded Intelligent Total Control System (ITCS) incorporates the culmination of three generations of continuous improvement in hydraulic controls and is "based on extensive customer input and product testing," according to Kobelco.

"ITCS recognizes the operator's moves and assists by providing power where and when it is needed. It also provides hydraulic sensitivity for fine grading and leveling," said Norwood. "The Mark 9 maximizes the capabilities of its Tier 4

"The Mark 9 maximizes the capabilities of its Tier 4 Interim-certified FPT engine and optimized hydraulics with the upgraded ITCS," said Reece Norwood, Kobelco Platform Manager.

Interim-certified **FPT** engine and optimized hydraulics with the upgraded ITCS."

Integrated swing priority, a Kobelco first, provides seamless and smooth transition of additional pump power to the swing function. Automatic hydraulic regeneration feeds the cylinder demanding oil first, with oil that is being pushed out of another cylinder. This requires much less energy than having to repump the oil again and also allows the next action to happen quicker. The independent travel feature, activated with a switch, dedicates a pump to travel motors for better movement while performing other functions, such as when handling pipe while moving to the trench.

Upgrades to the main valve and intelligent hydraulics, as well as new joysticks with proportional controls for the auxiliary hydraulics, contribute to the controllability upgrades of this new excavator.

"The Kobelco Mark 9 excavators set

the industry standard in terms of controllability, especially in multifunction applications," Norwood said. "Operators will appreciate the impressive control and smoothness of the SK210 Mark 9. The ease of operation makes a good operator a great operator and allows a novice excavator operator to be a good, productive operator."

The Power Boost feature on the SK210 Mark 9 delivers 10% more bucket breakout force on command, without time limit, while the Heavy Lift delivers 10% more lifting and swing capability on command, without time limit.

Several factory-available configurations are available for the excavators—including High & Wide, Long Reach, and Mass Excavation versions—and a choice of three undercarriage options. Heavy-duty frames, booms, arms, and undercarriages are standard on all the Mark 9 excavators.

The SK210 Mark 9 Long Reach, suitable for dredging and bigger ditch cleaning jobs, has a maximum reach of

52 ft (15.8 m). The SK210 Mark 9 High & Wide has a more stable stance, making it suitable for such applications as craning large pipe, loading out trucks, and scrap and forestry work.

An optional reinforced, severe-duty undercarriage is available for working in forestry, rock, or with single grouser track shoes. An optional special application package, featuring High & Wide undercarriage, reinforced frame, guarding, auxiliary hydraulics with extra rotation pump, and provisions for a cab riser, is available for above-ground applications such as forestry and scrap handling.

Additional features on the new Kobelco SK210 excavators include swing flashers and step extensions. Plug-in capability for telematics is standard on all Mark 9 excavators. All the excavators are compatible with grade control systems from leading suppliers to meet customer preference and applications.

A full selection of buckets, couplers, and thumbs is offered to maximize the machine's versatility.

Jean L. Broge

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Advertiser	Page
dSPACE Inc	3
MICO Inc	5

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