STEAM – a hydraulic hybrid architecture for excavators

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Abstract
During the past three years the Institute for Fluid Power Drives and Controls in Aachen has developed a new hydraulic system for mobile machinery called STEAM. The system represents a new step in excavator hydraulics, as it aims to reduce both the hydraulic system losses as well as those of the internal combustion engine by using a hybrid hydraulic architecture with accumulators. Starting with initial simulation studies the development has been followed by scaled test bench measurements and has progressed to a full scale validation using an 18 t excavator. The following publication aims to summarise the results obtained thus far with the aim of making them available to industry and encouraging their implementation in future applications.

KEYWORDS: Mobile Hydraulics, Hybrid Systems

1. Challenges facing improving system efficiency
Increasing the system efficiency of hydraulically operated mobile machinery has been the focus of much research in recent years. A number of new architectures have been proposed in literature, all with the aim of accomplishing the following four goals: reduce component efficiency losses (of the engine and pumps), decrease idling losses, avoid throttling losses and finally recover potential and kinetic energy from actuators.

The difficulty in designing a system that deals with all these separate factors is that addressing any one of them usually affects another negatively. A simple example to illustrate this dilemma is the use of so-called hybrid modules connected to the engine
shaft, which enable energy recovery but at the same time lead to increased idling losses /1, 2/. This complex system of tradeoffs is further complicated by the fact that for any new system to find acceptance in industry, it not only, has to be more efficient but should also not cost considerably more. In summary, the pursuit of more efficient mobile hydraulic systems can be described as an extremely challenging task with a set of even more restrictive boundary conditions. It is, therefore, no surprise that relatively few true innovations have found their way onto the market.

The STEAM mobile hydraulic system specifically designed for excavators is a possible way forward out of this stalemate. The idea is a simple one and in essence deals with each of the four above mentioned points by exclusively using low cost valves and widespread hydraulic accumulators. Naturally, the focus is on improved energy efficiency but beyond this STEAM also offers other interesting advantages, which give industry, and ultimately the customer, a few more reasons to consider using the new system. The following paper aims to summarise these advantages and presents the latest measurement results obtained from field tests.

1.1. The perfect solution in theory
An interesting question to begin with is whether a perfect system that reduces all major loss mechanisms, while enabling energy recovery, even exists. The surprising answer is that, yes, a near perfect hydraulic architecture does indeed exist, at least in the case of an excavator, a machine that nearly exclusively performs tasks, in which peak and average power demands greatly differ /3/. Figure 1 illustrates the setup, which is, in principle, a hydraulic hybrid system with a constant pressure rail and accumulator, a secondary controlled swing drive and hydraulic transformers to control the linear actuators.

Figure 1: Hybrid system with constant pressure rail and hydraulic transformers
A major advantage of the constant pressure system is that it decouples the supply side from the actuators, allowing optimal engine operation independent of the current power demand. As a result, the engine can be allowed to operate at a lower speed, 1200 rpm instead of the typical 1800 rpm, delivering only the average power demand, while the accumulators cover the peak power requirements. This so-called engine downspeeding considerably decreases losses /4/. Idling losses are also kept low as the pump swivels to zero displacement when the accumulator is full and no unnecessary losses occur. In addition, no throttling take place at all due to the fact that transformers are used instead of valves and all the potential and kinetic energy from the actuators can be transferred into the pressure rail to be reused later. In summary, basically the perfect system.

Well, perfect but only in theory as the practical implementation of such a setup is not feasible. The first and foremost problem is that no efficient hydraulic transformers are commercially available. The Dutch company INNAS has developed a prototype but has yet to get it onto the market /5/. Even if they were to do so the cost of this high-tech component compared to a standard mobile hydraulic valve would be considerably higher. The question that remains is whether it is possible to implement a modified version of this near perfect constant pressure system, by replacing the transformers with simple low-cost valves, but at the same time keep throttling low and allowing energy recovery. This question has been the topic of much debate and has been the starting point for researchers at IFAS in the development of the STEAM system.

1.2. STEAM – a possible way forward

STEAM is basically a hydraulic hybrid system that uses not only one but two pressure rails (high pressure HP and medium pressure MP) along with a series of simple valves to reduce the major loss mechanisms found in today’s mobile hydraulic circuits. One possible implementation is shown in Figure 2.

![Figure 2: A possible implementation of STEAM](image)
The rails along with their associated accumulators take care of peak power demands, thereby enabling more efficient engine operation in the lower 1200 rpm region /6, 7/. To minimise throttling losses when supplying flow to the linear actuators, a series of switching valves allows both pressure rails along with the tank line to be individually connected to both the piston and rod chambers of each cylinder. This setup creates a system of nine artificial supply pressures, which depending on the current load pressure, can be used to lower throttling losses but also to recover energy. A detailed discussion of all the possible operation modes can be found in /8/.

To control actuator motion any valve topology can be used. This includes the simple 4/3 way proportional valves, as shown in the figure, but can go as far as complex digital hydraulics valves, independent metering or single edge meter out control with pressure compensators /9/.

1.3. **STEAM – some interesting benefits**

As mentioned above, the most important benefit regarding efficiency is the improved engine and pump operation. Due to the fact that these components are only used to charge the accumulators, they are decoupled from the current actuator power demand and can therefore be used in a digital manner. When the accumulator state of charge (SOC) drops the engine and pump operate at full load. Once the accumulators are full the engine and pump are in idle. In this way the components never operate at part load conditions, which dramatically decreases losses.

STEAM also provides a solution to one of the major dilemmas hindering the implementation of boom potential energy recovery circuits, namely the issue of how to use the recovered energy in a meaningful and efficient way. Figure 3 illustrates the problem in more detail. As no load is usually present when lowering the boom the load pressure in the actuator is quite low, approximately 100 bar. As shown in (a) recovering this energy into an accumulator, precharged to 90 bar, is reasonably simple, but actually reusing this energy is quite difficult as the boom and the other actuators usually require a higher supply pressure during operation. Circuit (b) overcomes this issue by using a transformer. Unfortunately, this solution is quite inefficient due to the transformer losses. The STEAM circuit, shown in (c), can actively boost the boom rod side pressure to a higher level, thereby also increasing the boom piston pressure and allowing the energy recovery to take place at a higher pressure level of approximately 175 bar. Energy stored in this manner can be used to supply other actuators when needed.
A further benefit of the system is the ability to prevent pressure peaks in actuator end-stops. In order to completely empty the bucket during digging, excavator operators quite frequently drive the actuators all the way into the end-stop. When using a standard flow impressed system, i.e. load sensing or posicon/negacon, such movements cause a rapid increase in supply pressure all the way to the system’s pressure relief setting. This leads to unnecessary pressure peaks and throttling losses if other actuators are operated simultaneously. A constant pressure system avoids this issue as the actuator is supplied with pressure not flow.

2. System implementation and testing

One of the aims of the STEAM-Project is to bridge the gap between fundamental research and industrial application. In order to do so it is necessary to experimentally conduct representative fuel consumption measurements. This section describes how the system validation is being carried out.

2.1. Prototype excavator

In Europe, load sensing hydraulic systems have established themselves as the industry standard for excavators. Therefore, an 18 ton Volvo wheeled excavator (EW180C) with a Linde single-circuit load sensing system (LSCS) was selected as the benchmark for comparison /10/. To minimise the influence of external factors, which may distort the measurement results, the STEAM system was installed parallel to the LS system. This approach allows both systems to be measured on the same day using the same operator, thereby ensuring that the data from both measurements is comparable. A simplified schematic of the prototype machine is shown in Figure 4. Installing a secondary controlled swing drive was not possible as the machine only had a fixed displacement motor. To allow recovery of the swing brake energy, pressure controlled
sequence valves, connected to the accumulators, were installed. More details can be found in /6/.

--- STEAM ---- LS

**Figure 4**: Prototype machine layout

The actual machine with the new STEAM manifold block, containing all the switching and proportional valves, is shown in **Figure 5**.

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**Figure 5**: Prototype machine with STEAM manifold and accumulators

### 2.2. Test Cycles

It is not possible to compare the efficiency of two different hydraulic systems using just one value. Stating that one system is a certain number of percentage points more efficient than another is incorrect. Even when using the same machine with the same operator the efficiency will largely depend on the duty cycle. When operating only one actuator using standard LS-hydraulics very few throttling losses occur. During such operation newer systems can only operate marginally better or maybe even worse. The contrary is also true; it is possible to select operating conditions in which a new system
is considerably better than its older counterpart. Such comparisons are incomplete and lack a solid scientific grounding.

Therefore, it is only fair to judge two systems using a large variety of different cycles, a so-called cycle mix. This approach will be used to compare the LS-System to STEAM. The efficiency comparison will not be stated as one value but rather as a matrix. Such a representation can be used to conclude when and under which operating conditions STEAM is better than the standard system. Till date two fairly simple test cycles have been conducted. The first is a swing test, in which only the swing drive is used to rotate the machine back and forth. As discussed in /6/, these measurements show that STEAM is 39 % more efficient than LS. The improvement in efficiency is mainly due to the decrease in engine and pump losses.

3. Air Grading Measurement Results
The second test, which is the focus of this paper, is air grading and basically simulates common leveling operations. Both the boom and arm cylinders are operated simultaneously at maximum speed, see Figure 6. The air grading test closely resembles the Japanese JCMAS test cycle for excavators /11/. This section discusses the results of the air grading test.

![Figure 6: Air grading test cycle](image)

3.1. Fuel Consumption and Efficiency Comparison
Two factors must be considered when carrying out such a comparison. The actuator motion of both systems should be as similar as possible and the accumulators in the hybrid system must be charged before and after the test to ensure a fair comparison.
As shown in Figure 7 the measured actuator strokes for both systems are very comparable, although STEAM is evidently faster.

![Figure 7: Measured actuator displacement during air grading test](image)

The results of the test are summarised in Table 1. Despite the lower engine speed STEAM cut the cycle time by 11 %, performed 19 % more work, consumed 23,2 % less fuel and is 55 % more efficient.

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<td>x</td>
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<tr>
<td>STEAM 1200 rpm</td>
<td>0,89 x</td>
<td>1,19 y</td>
<td>0,768 z</td>
<td>1,55 y/z</td>
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Table 1: Efficiency and fuel consumption results

The significant increase in system efficiency is an important result but what is even more important and valuable is understanding what exactly is responsible for the improvement. To do so it is necessary to analyse the measurement data in more detail.

### 3.2. Actuator Operation

To begin with, it is interesting to take a closer look at the actuators and how they are supplied with flow. In the STEAM system, the individual actuators possess the ability to exchange flow with one another. Figure 8 illustrates the operating states of the boom and arm cylinders during air grading with STEAM. When moving from 1 → 2 the arm cylinder uses medium pressure regeneration (MP/MP), meaning the rod side supplies
the piston side with flow. During the return stroke 2→1 the boom potential energy is recovered into the medium pressure rail (as discussed in section 1.3), which then directly supplies the rod side of the arm actuator.

![Diagram of STEAM actuator states during air grading](image)

**Figure 8:** STEAM actuator states during air grading

This effect, along with the oil stored in the accumulators, allows the engine and pump to operate at a lower speed and only to supply the average power and flow. This is the major factor contributing to the improved system efficiency.

### 3.3. Engine and Pump Operation

**Figure 9** illustrates how often the engine operates at each torque/speed combination. The LS system, operating at 1800 rpm, shows one peak at high torque and full power when moving from position 1 to 2 during the cycle. On the return stroke (2→1) much less power is required, resulting in a more even distribution of the remaining operating points. None of these points are in regions of high efficiency, once again highlighting the poor utilisation of the engine characteristics in standard mobile hydraulic systems. Lowering the engine speed, which would improve efficiency, is not possible in these systems as no accumulator is present to supply peak flow, which is required when raising the boom and operating the arm cylinder simultaneously (1→2).

In comparison, using STEAM, the engine runs at 1200 rpm. This low speed high torque operation leads to considerably lower engine losses. In fact, measurements show that
around half of the total system efficiency improvement compared to LS is a direct consequence of the better engine performance.

Figure 9: Engine operation

Figure 10 shows very similar results in regard to pump efficiency. During LS operation the pressure is constantly changing depending on the current actuator load. When using STEAM the pump is used solely to charge the MP accumulator. Additionally, the displacement setting is also higher as the pump must swivel out more to provide the required flow at the lower engine speed.

Figure 10: Pump operation

4. Conclusion and Outlook

The STEAM system may be a possible way forward to meet the challenges facing the development and widespread usage of more efficient excavator hydraulic systems. Its
major advantage is the ability to considerably lower the engine speed, while maintaining the same performance as today's state of the art systems. Initial field tests are very promising showing a 39 % increase in efficiency for the swing drive and a 55 % increase in efficiency during air grading. Further testing is currently underway to test system performance in real digging applications.

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6. References


/7/ Leifeld, R., Vukovic, M., Murrenhoff, H., STEAM – the best of both worlds, 7th Workshop on Digital Fluid Power, Linz, Austria, 2015.


7. **Nomenclature**

\( MP \) Medium Pressure \( \text{bar} \)

\( HP \) High Pressure \( \text{bar} \)