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Reducing Energy Consumption of Hammering With Electric Excavators

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TIIVISTELMÄ

Iskuvasaroinnin energiankulutuksen pienentäminen sähköisellä kaivinkoneella

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Tämän työn tavoitteena on tutkia tapoja, jolla iskuvasaroinnin energiankulutusta pystytään pienentämään sähköisellä kaivinkoneella. Iskuvasaroinnin energiankulutuksen ymmärtämiseksi työssä perehdytään perinteisen kaivinkoneen rakenteeseen ja energiankulutukseen. Perinteiseen kaivinkoneeseen perehtyminen luo myös pohjaa sähköisen kaivinkoneen toiminnan ymmärtämiseen. Sähköinen kaivinkone ei ole vielä yleisesti käytetty laite, joten sen eri toimintaperiaatteita käsitellään tässä työssä. Erilaisia teknologioita esitetään siihen, kuinka sähköä voidaan hyödyntää iskuvasaroinnissa. Iskuvasaroinnin energiankulutusta tutkitaan myös kokeellisesti. Tehohäviömittaukset iskuvasaroinnissa tuovat esiin tämän hetken ongelman kaivinkoneen hydrauliikkajärjestelmässä ja kaivinkoneen käytöstä iskuvasaroinnissa. Mittausten lisäksi työssä suunnitellaan sähköenergiaa hyödyntäviä iskuvasarakonsepteja. Konsepteja arvioidaan sekä energiatehokkuden kannalta että laadullisesti.

Mittaustulokset tuovat esiin hydraulisten häviöiden suuruuden. Eri tyyppisissä iskuvasaroinnissa tehohäviöt ovat eri suuruisia johtuen kaivinkoneen hydrauliikasta. Eri konseptit tuovat suurta potentiaalia energiankulutuksen pienentämiseen sähköä hyödyntäen. Konseptit tarjoavat myös uusia ominaisuuksia rikotukseen. Konsepteissa käytettäviin teknologioihin pitää syventyä jatkossa vielä tarkemmin ja halutut laadulliset ominaisuudet tulee määrittää. Mittaustulokset osoittavat häviöiden suuruuden, mutta energiankulutuksen mittaamiseksi tulisi määrittää työsykli iskuvasaroinnille.

Asiasanat: sähköistyminen, iskuvasara, energiankulutus

ABSTRACT

Reducing energy consumption of hammering with electric excavators

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The aim of this master's thesis is to research methods to reduce the energy consumption of hammering with electric excavators. To understand the energy consumption of hammering, the structure and energy consumption of a conventional excavator is explained thoroughly. The knowledge of a conventional excavator also lays foundation for studying the electric excavator. An electric excavator is not yet a widely used machine so different operating principles and models are presented in the work. Different technologies are described for utilizing electricity in hammering. Energy consumption of hammering is researched by measurements of the current situation. Measuring the power losses in hammering brings forward the challenges in the conventional hydraulic system and the excavator use in hammering. In addition to the measurements, hammer concepts are designed utilizing the technology researched. Quantitative and qualitative properties of the concepts are reviewed.

The size of the power losses of hammering can be seen in the results of the measurements. The magnitude of the losses depend on what type of hammering work is done. The different hammering concepts bring large potential in reducing the energy consumption. The concepts also have new features, which can affect the productivity. The technology used in the different concepts still needs to be researched more and desired features determined. The measurements show the magnitude of power losses in this excavator, but a working cycle should be determined to measure the energy consumption.

Keywords: electrification, energy efficiency, hammer

PREFACE

This master's thesis was done during 2021 at Sandvik Mining and Construction Oy in Lahti. The supervisors of this work were Dr. Toni Liedes (University of Oulu) and Chief engineer Erik Airas (Sandvik). I would like thank them for their support and genuine interest in supervising the thesis. I would also like to thank Sandvik Lahti R&D department for enabling the meaurements performed and the support on this thesis. Warmest thanks to my closest friends for being there for me, no matter what. Lastly I would like tothank my family for the continuous support and motivation.

Lahti, 27.10.2021

Samuli Korhonen
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SYMBOLS AND ACRONYMS

A_{Piston}	Cylinder piston side area
A_{Rod}	Cylinder rod side area
E	Output energy of the hammer
E_{p}	Piston kinetic energy at moment of impact
f	blow frequency
m_{p}	Piston mass and
P_{Act}	Power of the actuator
P_{Throttle}	Power loss in the valve
p_{L}	Load pressure
p_{Piston}	Cylinder piston side pressure
p_{Rod}	Cylinder rod side pressure
p_{R}	Return line pressure of the hammer
p_{s}	Supply pressure of the hammer
Q	flow passing through the valve
Q_h	Supply flow rate of the hammer
Q_{L}	Flow required by actuator
v_{p}	Piston velocity at moment of impact

η_{tot}	Total output efficiency of the hammer
Δp	Pressure difference between the valve orifices

ERS	Energy regeneration system
JCMAS	Japan Construction Mechanization Association Standard
LS	Load sensing
PMLM	Permanent magnet linear motor
SR	Switched reluctance

1 INTRODUCTION

Environmentally friendliness and energy saving have risen in demand concerning industries like the automotive industry. Electrification of vehicles has become a popular trend to answer this demand and relevant technology has been established in the automotive industry. This trend of electrification is starting to emerge in the construction machine industry as well. Constantly tightening emission laws and pressure from the public to be more environmentally friendly drives the development of electrified construction machinery forward. Construction machines, such as hydraulic excavators, have been working with high fuel consumption and pollution to maintain the work performance, controllability and reliability in fluctuating load conditions.

The hydraulic excavator is a highly versatile machine used in multiple different tasks. It consists of a diesel engine, which powers a hydraulic system. Multiple hydraulic actuators are powered by the hydraulic system and can include auxiliary attachments like the hydraulic hammer. The hydraulic system exhibits fluctuating loads because of the nature of the work done by excavators (Vukovic 2017). The hydraulic excavator demands high power from the actuators which leads to high energy consumption. The efficiency has been stated to be low in a hydraulic excavator. Total efficiency of consumed output energy at the actuators relative to the delivered hydraulic energy is in the range of 15 % to 25 % (Hießl 2015). This excludes the diesel engine, which has an efficiency of approximately 40 % (An 2020). Construction machine manufacturers have started to electrify the excavators by substituting the diesel engine with an electric motor to drive the hydraulic pump. The hydraulic system can be left as is, but there is desire to improve the inefficient conventional hydraulic system. The actuators can be directly driven by a pump and motor using zonal hydraulics. Zhang et al. (2017) study showed an efficiency of 71.3 % for the zonal hydraulics compared to 18.3 % by the conventional system. The hydraulic system can also be changed in to a common pressure rail system, which can improve the fuel efficiency 34–50 % (Heybroek 2018). The limited electrical energy storage used by the motor adds demand on the efficiency of the whole system to achieve satisfactory working times.

The hydraulic hammer attachment demands high power from the hydraulic system of the excavator. The energy consumption in hammering work needs to be minimized to obtain longer work times and efficient use of an electric excavator. The electric excavator also brings a new source of power that could be utilized in excavator attachments.

The aim of this thesis is to research existing technology to minimize energy consumption of hammering. Understanding the excavator's system gives knowledge to reduce the energy consumption of the machine. Studies have been conducted on excavator's energy efficiency and losses in the hydraulic system by Zimmerman et al. (2007), Vukovic et al. (2017) and Casoli et al. (2020), but they have restricted to only digging and trenching work. This sets the measurement of the current system as another target of this thesis. Energy efficiency and power losses of the hydraulic system will be measured in hammering work to establish the current state. With the technology researched to utilize the electric power source in hammering, concepts of different electric hammers will be reviewed. The objective is to find concepts to minimize the energy consumption of hammering. Finding different types of concepts will lay ground for future studies.

As will be discussed in chapter 2 the power losses in the excavator are large in digging and trenching. The current state measurements will show how hammering work relates to typical excavator work. A hammer manufacturer like Sandvik does not have the ability to directly affect the structure of the carrier a hammer is being used on. The measurements will give perspective on how much of the total efficiency is due to the hammer and what approaches should be taken to reduce the energy consumption. The concepts will give an overall view but the efficiency being a key part. The use of electrical energy should result in improvements due to the large losses in the hydraulic system.

The thesis consists of a literature review, measurements and concept review. In chapter 2, the background of the hydraulic excavator is laid out. Concentrating on the hydraulic system, the main causes of energy consumption and losses are explained. Chapter 2 also includes a review of the current state and research in to electrifying the excavator. Chapter 3 focuses on the hydraulic hammer. In chapter 4, technologies that could be utilized for electrifying the hammer are discussed. The measurements and the results are presented in chapter 5. Chapter 6 focuses on concepts for electrifying the hammer. The concepts are reviewed for their qualitative and quantitative properties. In chapter 7 the results of the measurements and the hammer concepts are discussed.

2 HYDRAULIC EXCAVATOR

The object of this chapter is to give an overview of the hydraulic excavator. The main working principal of a modern hydraulic excavator will be explained. The advantages and disadvantages of the machine are explained to understand the challenges concerning energy consumption. The future of hydraulic excavators will also be discussed to get a view of how the technology is changing in the field and how it affects the equipment of the excavator

2.1 Development of hydraulic excavator

The first excavator was made in 1838. It was steam powered and the operation of the arm was mechanically controlled with cables (Yang 2011). As the technology improved, the machine became larger and the crawling mechanism was changed to be more environmentally friendly. Hydraulics came in to play in 1948 to replace the mechanical cables. (Yang 2011) Until this point, the excavators had been either fully mechanical or a hybrid of steam, cables and hydraulics. The first fully hydraulic excavator gave a significant advantage over the mechanical ones. Power density, controllability and efficiency are some of the great properties of hydraulics that led it to replace the mechanical counterparts. These properties made the machines smaller and more accessible in construction sites. The fundamental structure of the excavator remains the same to this date. It consists of the undercarriage, upper structure and front attachment. The front attachment includes mainly the boom, stick and arm. The hydraulic system has been under constant fierce development to improve important aspect such as controllability and energy efficiency. (Yang 2011)

The hydraulic excavator has reached a significant position in the construction machinery world. It is one of the most used machines. The popularity comes from its versatility. The main task could be considered digging with a bucket attachment on the front hoe. The large size range, from a small 1-tonne micro excavator to a 1000-tonne mining excavator, gives the ability to use it in different places. In addition to a bucket, there are multiple different attachments with different applications to widen the use of an excavator. Popular attachments include demolition tools, such as hydraulic hammers, hydraulic pulverizers and shears, but also construction tools, such as augers and grab attachments.

The excavator has not fundamentally changed in the last 50 years. The structure consists of the undercarriage, upper structure and the front attachment. As seen in Figure 1, the undercarriage consists of the tracks and the blade. The tracks can also be replaced by wheels. The upper structure holds the cabin, engine, hydraulic power source and the control system. It is also able to rotate in relation to the undercarriage. The front attachment is attached to the upper structure. The front attachment typically consists of the boom, stick or arm, and the bucket.

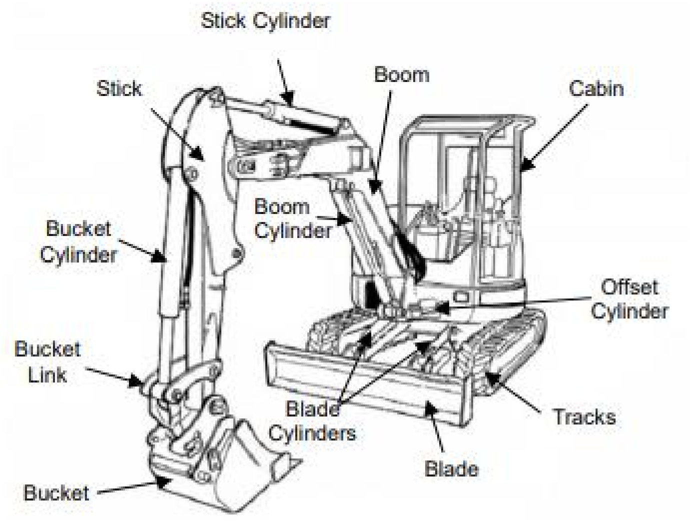

Figure 1. Excavator structure (Zimmerman 2017)

Pressurized flow is provided by one or more hydraulic pumps. The pump is powered by a diesel engine. A series of directional valves is used to distribute the pump flow. This is commonly referred to as the main control valve. The operator can manipulate the main control valve using joysticks in the cabin. (Vukovic 2017) The joystick allows for an intuitive distribution of the flow to all the actuators needed for work. Hydraulic cylinders on the boom, stick and bucket allow for the movement of the front attachment and hydraulic motors are used for the swing motion and travel drive.

A load sensing hydraulic system is considered the state of the art in excavators. A load sensing system is simply a system which provides only the pressure and flow needed at the moment. (Alvin 2012) It replaced the constant flow system for better efficiency but still maintaining robustness and controllability. A load sensing system requires a variable displacement piston pump with a compensator. The compensator allows the pump to standby at low pressure when the system is not being used. The system senses the flow requirements of the actuators and provides variable amounts of flow depending on the need. The system also senses pressure. Pressure sensing is needed because the pressure of the system changes depending on the load of the system. The main control valve needs extra passages for the pressure sensing. When the pressure of an actuator changes, the control valve will send a signal to the motor. The motor then reacts appropriately by changing the system pressure. The pressure signal from the actuator is needed only when the actuator is in use. When the control valve is not active, the valve needs to send a signal for the pump to go to low pressure standby mode. The requirement is dictated by the valve spool. The system detects the flow requirement of the actuator and sends a signal to the pump. This allows the variable speed of the actuators. (Alvin 2012)

2.2 Energy consumption

The need to reduce fuel consumption and emissions has led to multiple studies on the fuel consumption of hydraulic excavators. The efficiency of a hydraulic excavator has been stated to be fairly low. The total efficiency of consumed output energy at the actuators relative to the delivered hydraulic energy is in the range of 15 % to 25 %. (Hießl 2015) To understand the energy consumption, the flow of power and the losses at each stage must be understood. The power flows from the combustion engine, through the hydraulic pumps to the actuators. Losses occur at each stage and between stages.

In figure 2 the location of the losses is shown. The first source of loss occurs in the engine and pumps. Converting energy from one form into another results in losses. Hydraulic losses result from mainly throttling losses in the control valves. Ancillary drives include functions of the machine such as cooling steering and breaking. These are considered losses because they do not directly contribute to the execution of the required task but consume energy (Vukovic 2017).

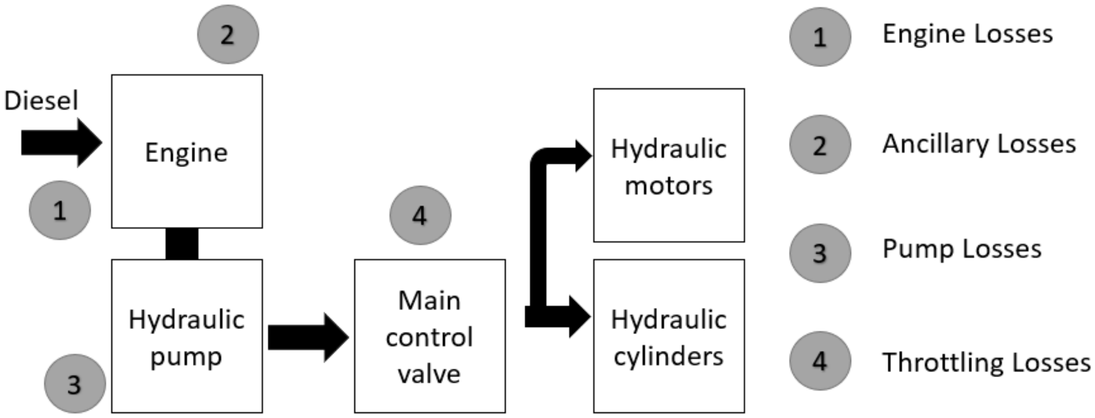

Figure 2. Flow of power

The internal combustion engine is the first stage of loss in the system. The use of diesel fuel generates heat and losses in the conversion from chemical to mechanical energy. According to Vukovic et al. (2017), the typical maximum efficiency of a construction machine engine is just over 40 %. This value is highly dependent on the engine torque and speed. In a study conducted by An et. al (2020), a typical dig and dump working cycle was analyzed for energy consumption. The results showed 40.2 % of the fuel energy was converted by the engine to the main pump. This low efficiency leads to high fuel consumption, which raises cost and emissions. Excavators are frequently operated at fixed engine speed in order to deliver peak power. The speed for peak power is usually different from peak efficiency. (Vukovic 2017) The core of the issue is the performance the excavator requires. In a duty cycle of an excavator, the engine load fluctuates immensely and a quick response to load changes must be achieved. These transient loads have a large effect on the fuel consumption (Vukovic 2017). The load pressure and pump displacement vary constantly, which leads to fluctuation in the engine load torque. Part loading is inefficient engine use. Considering the total amount of energy consumed, idle time, during which no work is done, still consumes energy. Parasitic losses in the engine lead to energy consumption while the machine is in the idle state.

The hydraulic system faces a problem with the complexity of the loads in the actuators. Each actuator needs individual force and velocity control. Furthermore, the requirements for each actuator varies largely. In some cases, high pressure and low flow might be required and, in other cases, low pressure and high flow might be needed. The loads on a cylinder may be illustrated in a quadrant model. The four quadrants can be seen in Figure 3. The flow required by each piston is on the x-axis. The load pressure on the y-axis can be calculated as follows (Vukovic 2017):

$$p_{\mathrm{L}} = p_{\mathrm{Piston}} - \frac{A_{\mathrm{Rod}}}{A_{\mathrm{Piston}}} \cdot p_{\mathrm{Rod}} \tag{1}$$

where p_{L} is load pressure [Pa],
p_{Piston} is cylinder piston side pressure [Pa],
A_{Rod} is cylinder rod side area [m^2],
A_{Piston} is cylinder piston side area [m^2],
p_{Rod} is cylinder rod side pressure [Pa].

Using the pressure and the flow, the power of the actuator is:

$$P_{\mathrm{Act}} = p_{\mathrm{L}} Q_{\mathrm{L}} \tag{2}$$

where P_{Act} is the power of the actuator [W],
Q_{L} is the flow required by actuator [m^3/s].

The movement of the actuator and the force of the load dictate the quadrant in which the actuator is operated upon. In quadrants 1 and 3, the actuator experiences a resistive force relative to its motion. In quadrants 2 and 4, the force is assistive, helping the motion of the actuator. This means that, in quadrants 1 and 3, there must be power supplied, whereas, in quadrants 2 and 4, actuators can supply power to the system. The boom cylinder often operates in only quadrants 1 and 2 because of the kinematics of the machine. The arm and bucket cylinders and the hydraulic motor operate in more various ways, causing operation in all four quadrants. (Vukovic 2013)

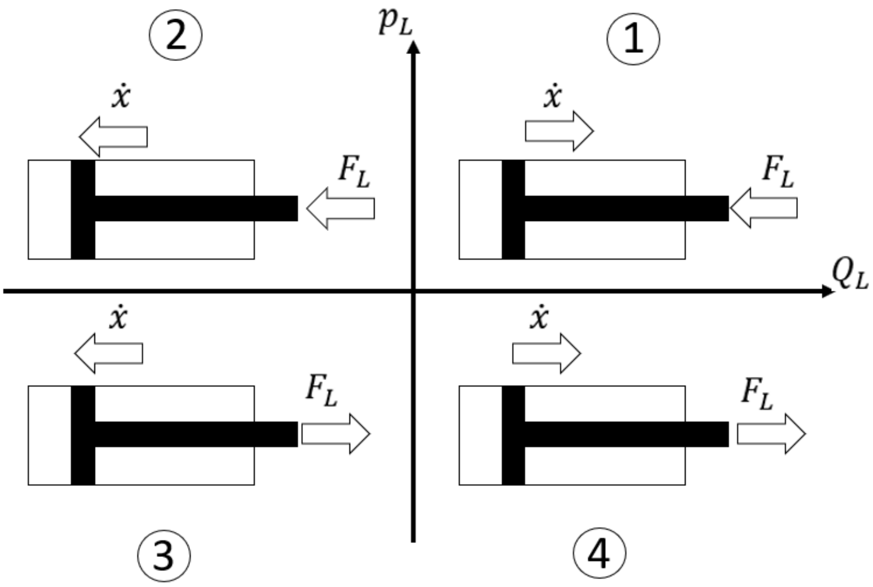

Figure 3. Cylinder four quadrant model

The hydraulic pump converts the mechanical output power of the engine to hydraulic power in the form of flow and pressure. The losses of the pump consist of hydro-mechanical losses and volumetric losses. Hydro-mechanical losses are formed by mechanical and fluid friction. It is determined by the theoretical torque required to drive the pump divided by the actual torque to drive it. Volumetric losses can be determined by dividing the measured flow of the pump by the theoretical flow. These losses are caused by leakages in the pump. (Heybroek 2017) The overall efficiency is the product of the volumetric and hydro-mechanical efficiency. A typical pump used in excavators is a variable displacement piston pump. The efficiency of a pump of this type varies between 60 % and 90 % (Vukovic 2017). The overall efficiency drops when displacement and pressure is low. In an experimental study by Xu et al. (2016) the overall efficiency of a variable displacement piston pump was measured with different displacement ratios and pressure levels. The displacement ratios varied from 13 % to 100 % with pressure levels from 5 to 35 MPa and speeds of 1000 and 2100 r/min. A maximum overall efficiency of 90 % was measured with full displacement at 1000 and 2100 r/min. As seen in Figure 4, a decrease in speed from the rated speed of 2100 r/min to 1000 r/min increases the size of the low efficiency area. The high efficiency area also decreases and shifts to a lower pressure zone.

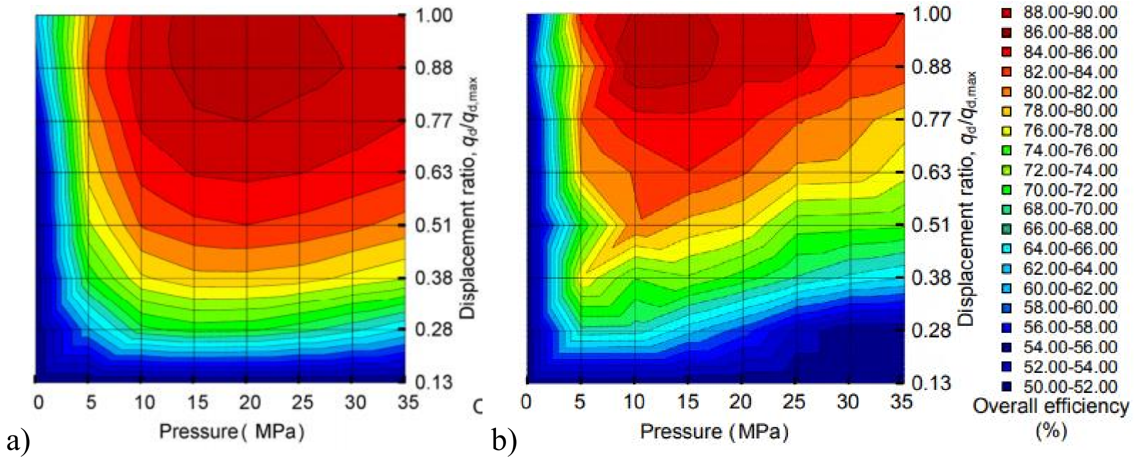

Figure 4. a) Overall efficiency of pump at 2100 r/min and b) Overall efficiency of pump at 1000 r/min (Xu 2016 reprinted with permission)

The power from the pump is distributed to the actuators by valves. A pressure difference between the two orifices of the valve is needed for flow to pass. The pressure difference depends on the valve’s geometry and the spools position. Hydraulic power entering the valve is lost as heat. These losses are called “throttling losses” and can be expressed with the following equation:

$$P_{\text{Throttle}} = Q\Delta p \tag{3}$$

where, P_{Throttle} is the power loss in the valve [Pa],
Q is the flow passing through the valve [m^3/s] and
Δp is the pressure difference between the valves orifices [Pa].

If a valve is designed properly, the throttling losses can be minimized to an acceptable level. The problem with throttling losses occurs in the nature of the excavator hydraulic architecture. A single pump providing flow to multiple actuators distributed by valves is challenging. In order to deliver flow to each actuator, the system pressure level must exceed the actuator pressure levels. (Vukovic 2007) To save energy, the pump supply pressure in the LS system is adjusted to match the highest pressure of an actuator in use. However, other actuators may have a lower demand of pressure. To lower the pressure, the flow is metered through control valves and this causes the undesired throttling losses. The simultaneous operation of multiple actuators is a significant factor in the power losses. (Zimmerman 2007)

As stated earlier, the excavator is a versatile machine which can perform various tasks. To evaluate the excavator's energy consumption during operation, fixed conditions are required. A work cycle must be determined for tests to get repeatable and comprehensive results. A dig and dump cycle is a common work cycle used in studies. It is a common work duty for excavators and excludes secondary functions that do not directly contribute to the work. For example, the Japan Construction Mechanization Association Standard (JCMAS) has a dig and dump working cycle which can be used for fuel consumption measurements (JCMAS 2007). In a study by An et al. (2020), the energy consumption of each component of the excavator was measured during a work cycle. Similar studies have been conducted by Zimmerman et al. (2007), Vukovic et al. (2017) and Casoli et al. (2020).

The energy consumption of a work cycle can be presented in a Sankey diagram. The energy consumption of each component can be seen, and the final percent of energy utilized in the work. In Figure 5, a Sankey diagram of the energy consumption measured by An et al. (2020) is shown. The majority of the energy from the fuel is consumed by the engine. Only 40.2 % of the fuel's energy is transferred to the pump. Over twenty-two percent (22.4 %) of the mechanical energy is lost in the conversion to hydraulic power by the pump. The main control valve transfers 78.4 % of the hydraulic energy to the hydraulic motor and cylinders. This means only 23.2 % of the total fuel energy is transferred to the actuators. Disregarding the engine losses of 60 %, only 45.5 % of the energy generated by the engine is transferred to the actuators.

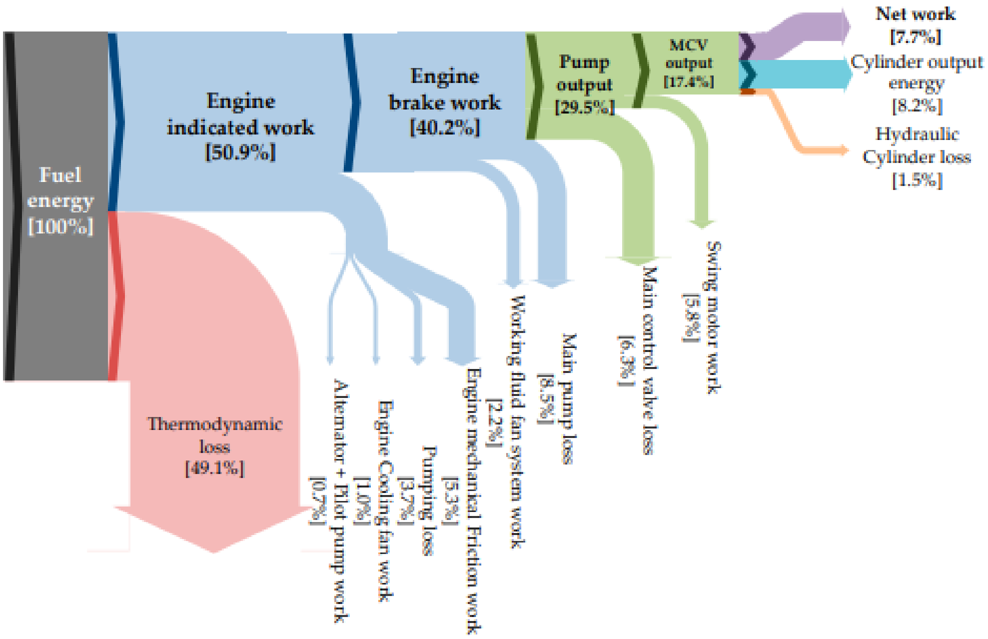

Figure 5. Sankey diagram of a dig and dump cycle (An et al. 2020 reprinted with permission)

2.3 Energy saving solutions

Alternative solutions to the conventional excavator system have been studied to deal with the low efficiency of the machine. Pressure from constantly tightening emission laws are also driving manufacturers to develop more efficient excavators. Excavators emit the most CO_2 out of all the construction machines. About 50 % of the CO_2 emissions of construction machinery in Japan are caused by excavators (Ohira et al. 2013). In the United States, 15 % of the emissions from non-road construction machines are caused by excavators (Dallmann et al. 2016). Emissions of non-road vehicles are regulated by the EPA in the United States and the EU in Europe. The regulations aim to lower pollutants, including NO_x, PM, HC, CO and smoke, by better engine design and exhaust treatment. (Dallmann et al. 2016) Another large contributing factor for improving the efficiency is to lower fuel consumption. Operating costs have the greatest impact on the full cost of the machine, which is comprised of operating costs, property costs and administrative costs. fuel costs are a significant part of the operating costs. (Chaves 2016) So, in addition to the pressure to reduce emissions, the need to reduce overall costs is also driving the study for more efficient excavators.

2.3.1 Hydraulic system

Improving the hydraulic system to reduce losses can lead to higher energy efficiency. Bedotti et al. (2017) proposed methods to save energy in the current excavator system using a load sensing (LS) system. Dividing the actuators into two different groups using two LS pumps is effectively a solution to reduce losses in the system. The groups are separated by coupling actuators that do not operate simultaneously. The fuel saving was calculated to be around 6 %. However, the downside of this application was an increase in installation space and cost. Another way to save energy on the current LS system is by reducing the margin pressure of the pump. For the LS system to work properly, there must be a pressure difference between the pump outlet and the load sensing pressure. This is called the margin pressure. The margin pressure affects the performance of the machine. If reduced too much, the movements get slower and the machine is not as responsive to the operator. A moderate change in the margin pressure can improve the energy savings enough to justify the decrease in performance.

There have also been different hydraulic systems proposed to replace the LS system. Research has been done on decentralized hydraulics by Zhang et al. (2017). In the research, the boom, arm and bucket of a micro excavator were controlled by three direct driven hydraulic units instead of valves. The efficiency of the system was compared to an LS control system. The results showed an efficiency of 71.3 % by the direct driven hydraulics and 18.3 % by the LS control.

A common pressure rail (CPR) system has also been introduced as an alternative hydraulic system. It generally consists of two pressure lines with a pump to provide the pressure and an accumulator to store energy and supply pressure as needed. The common pressure rail system benefits from high energy recovery capabilities which enables downsized power units. However, the control has not reached a level for implementation in an excavator yet. The system needs hydraulic transformers or pressure boosters to transform the constant supply of pressure required for the actuators. These components are not currently available. (Mahata and Ghoshal 2020) Another technology to help utilize the CPR in excavators is the variable displacement linear actuator or multi-chamber cylinder. The cylinder has multiple chambers compared to two chambers in a conventional cylinder. In a four-chamber cylinder two positive forces are opposed by two negative forces. The pressure applied to each chamber determines the force output of the cylinder. When all four cylinders areas are different and the CPR contains two pressure levels, 16 different combinations can be achieved (Heybroek 2018). This allows 16 different force levels for the cylinder. Heybroek and Sahlman (2018) simulated an excavator with variable displacement linear actuators and a CPR system and compared it to a hybrid design with a conventional hydraulic system. The systems were tested in a typical truck loading cycle. A 34–50 % improvement in fuel efficiency was measured. The dispersion results from differences in operator working styles. With this system there is no need for the main control valve used in traditional hydraulic systems.

2.3.2 Hybrid designs

Hybrid technology has been seen in commercial cars from the late 1990's. In construction machinery, the first hybrid entered the market in 2008. However, the different requirements for a construction machine make it harder to utilize hybridization.

Hybrids can be categorized in many ways but one of the most common ways is into series hybrid or parallel hybrid (Figure 6). This refers to how the additional energy source is arranged relative to the main source. These can also be mixed where one part of the machine works in parallel and another in series. (Heybroek 2017) For example, in a series structure, the combustion engine is connected to a generator and the kinetic energy is converted into energy storage or directly used by the inverter. Series structure has positive features in fuel efficiency and ease of operation, but the structure is complex and hard to make efficient. Parallel hybrids use at least two power sources together. (Heybroek 2017) For example, an electric motor can be used in parallel with a combustion engine to shave off the peak loads while working. This can, in some cases, lead to downsizing of engines and reduce fuel consumption and emissions.

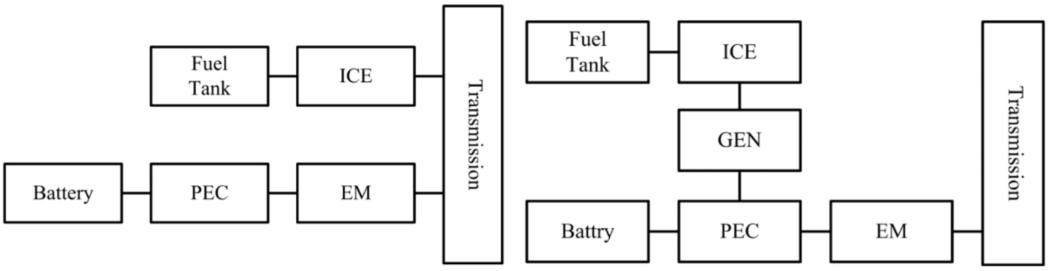

Figure 6. Series and parallel structure for hybrid

A key part of hybridization is the ability to regenerate energy. The regeneration comes from the recovery and reuse of the potential energy of the loads and the kinetic energy from decelerating inertia loads. (Heybroek 2017) The energy is stored in an energy storage device, from which it can be reused. Currently, the main options for the energy storage are batteries, supercapacitors and hydraulic accumulators. A hydraulic hybrid machine employs a hydraulic accumulator. The hydraulic accumulator stores the recovered energy in hydraulic form and releases it using secondary components or auxiliary cylinders. (Wang 2016) The hydraulic accumulator has a good power density, but the energy density is limited. There must be a compromise over the energy storage capacity and the volume or weight. The accumulator is ideal for a short work cycle consisting of multiple starts and stops. The energy efficiency of the hydraulic is good at almost 90 % and it does not need complex power controls compared to the electric counterparts.

2.3.3 Pure electric excavator

The adaptation of pure electric drive in construction machinery is intriguing for both its environmental benefits and dynamic benefits. It is pollution free with no emissions, and the noise pollution is lower than with the internal combustion engine. A pure electric construction machine uses an electric motor and an electric power supply. The advantage of an electric motor is its high efficiency. A vehicle with an electric motor also requires less maintenance than one with an internal combustion engine. The aspect holding back pure electric construction machinery is the energy storage. The energy storage can be achieved through batteries, fuel cells or supercapacitors. However, the charging and endurance of the storage system is limiting the widespread use of an electric power source. All-electric vehicles have been used with external grid power sources, but that severely limits movement and the location of the work. So, the development of all-electric is tied to the development of the energy source. The requirements of a construction machine are higher than the ones in automotive industrial use. More is required from the electric motor in regard to dynamic performance, speed range, overload capacity and safety. (Lin et al. 2021)

Pure electric excavators are already entering the market as battery-powered excavators. Different manufacturers have released micro excavators promising a full 8 hours of work with one charge or multiple shorter charges. Caterpillar has been the first to develop and sell a 26-tonne, battery-powered excavator to Norway, promising 5-7 hours of continuous work (Lambert 2019, Randall 2019). These machines have basically replaced the internal combustion engine with an electric motor and battery pack. The hydraulic system stays relatively same with a valve-controlled system. The electric vehicles include regeneration methods for more efficient use. Volvo has been the first to release a concept for a decentralized hydraulic system used in an electric excavator. The cylinders in the excavator are replaced with pump-controlled hydroelectric systems. This is still in development and has not been scaled to larger models.

One of the biggest challenges in an electric hydraulic excavator is the energy storage unit. There are multiple types of storage with different properties such as lithium battery, supercapacitor and hydraulic accumulator. The energy density, power density and cycle life are key values in an energy storage unit. The fluctuation of loads in an excavator are a challenge for the storage unit as well. The supply needs to last for at least an entire workday. In addition, it must tolerate the high forces applied on the excavator. The lithium battery has a high energy density, which means it can hold large amounts of energy in a smaller space. This is crucial for long-lasting, compact storage. However, the power density of a lithium battery is not as good. The fluctuations of loads occasionally call for high power and, therefore, lithium batteries do not perform well in these conditions. (Lin et al. 2021) For example, a hydraulic breaker requires high power in small bursts. Coupling a battery with a high-power density storage unit would be a considerable choice. For example, using a hydraulic accumulator or supercapacitor to react on the dynamic, high-power needs improves the system. Therefore, the battery is not strained by high power loads and can ensure the working time, while the hydraulic accumulator ensures the dynamic response. The addition of multiple storages lead to more complex control systems and harder implementation.

The most common electric motor used in construction machines is a permanent magnet synchronous motor (PMSM) and asynchronous motor. The PMSM has an advantage over asynchronous motor in high power density and torque density. These qualities are important where installation space is limited. The asynchronous motor is low cost, reliable, convenient maintenance and can stand a large change in operating temperatures. The larger size and weight make it compatible with larger sized machines.

Switched reluctance (SR) motors are also attracting interest for their lack of rare earth materials. SR motors have high efficiency, a simple structure, low cost and good reliability. (Lin et al. 2021) However, there are issues, such as torque ripple, noise and vibrations, in SR motors which do not make them a viable choice at the moment.

The electric motors speed regulation performance compared to a diesel engine is better. The dynamic response, speed control accuracy and overload capacity are for example superior to a combustion engine. The problem with electric excavators is the utilization of these features. The electric motor is used to simulate the engine in current machines. This doesn’t allow the features to show effectively. The ability to sense the system load of an excavator is present but the use of variable speed control is harder to implement. With variable speed and variable displacement, the pump and motor could run at the highest efficiency. (Lin et al. 2021)

Energy regeneration systems (ERS) contribute in making a hydraulic electric excavator more energy efficient. The electric storage and power allow the regeneration of electricity, but hydraulic energy regeneration is a valid method as well. The nature of an excavator does not allow for the same regeneration methods as with wheeled mobile machines. The traveling movement is accomplished by hydraulic motors and it is not efficient to convert it into electric drive for crawlers. A common ERS implementation is seen in the boom and swing system. The boom is usually heavier than the weight of the load and the potential energy can be recovered while moving the boom down. In the swing motion of the upper mechanism, the breaking process can be recovered. The challenge in ERS is to maintain the sufficient handling and safety properties of the motion.

3 HAMMER ELECTRIFICATION

In this chapter, technology for utilizing electric power in hammering is reviewed. First the conventional hydraulic hammer is introduced. An overview of the main tasks performed by a hammer is provided and the operating principle is explained. The primary components of a hydraulic hammer are presented, and the properties required from a hydraulic hammer are discussed. The chapter continues by presenting different types of technology for the utilization of electric power in hammering. The speed and force requirements of the hammer are challenging. Electric power can be directly or indirectly used to power the hammer. With direct use of electric power, hydraulics can be eliminated from the application. Electric power can still also be used with a hydraulic hammer to improve the system efficiency.

3.1 Conventional hydraulic hammer

Hydraulic hammers, which are often also called “hydraulic breakers”, have applications in many branches of industry, such as mining, civil engineering and metallurgy. In mining and quarrying, hydraulic hammers are used for mining without blasting, secondary breaking of oversized boulders and quarrying. Demolition of concrete structures and road surface removal are tasks for hydraulic hammers in the construction industry. In the metallurgy industry, it can be used for the removal of hot slag and refractory material. In urban areas, hydraulic hammers are a reasonable alternative to explosive techniques. They also bring safety advantages over explosives in the work site. The hydraulic hammer’s wide range and performance in adverse working conditions create high demand for the hammer’s properties. It must be reliable and durable to endure the harsh working environments. (Sokolski 2019)

In the 1960’s, the first hydraulic hammers were developed for concrete breaking and rock mining. After over 50 years of development, there is a large range of hammers with operational weights ranging from 50 kg to over 10,000 kg. The hammers can be used with small micro excavators or demolition robots, as well as with large heavy-duty excavators.

(Sokolski 2019) The large range of carriers and the high utilization of the hydraulic hammer has led to the development of such a wide size range. The designs of different manufacturers may vary, but they have common characteristics in the working principle. Namely, a hydraulic hammer is composed of a valve to distribute hydraulic oil, an accumulator, a piston and a tool which are encased in a frame. (Park 2006) One configuration of a hydraulic hammer can be seen in Figure 7.

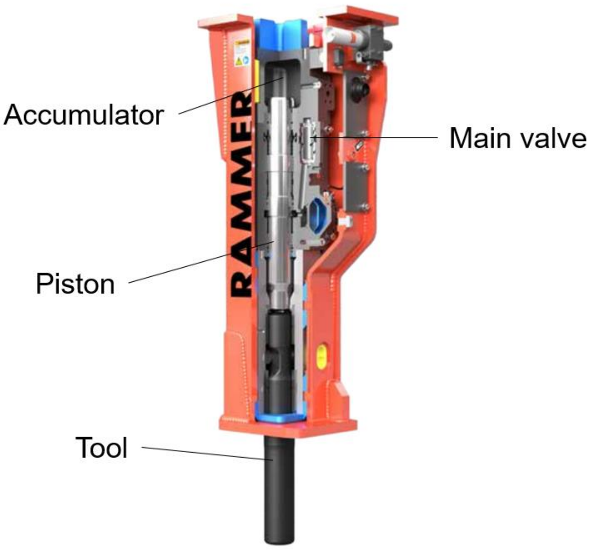

Figure 7. A hydraulic hammer

The basic idea of the hydraulic hammer is to convert the hydraulic energy provided by the excavator into energy to break a target material, such as rock. The hydraulic energy is converted into the kinetic energy of the piston. The piston is accelerated at high speed to impact the top end of the tool. The impact process causes the kinetic energy of the piston to be converted into stress wave energy in the tool. The stress wave propagates through the tool into the target to be broken. (MBMB 2006)

The return stroke of the piston is similar in most designs for hydraulic hammers, but there are differences in the working stroke. The valve directs pressurized oil in a chamber to drive the piston up. When the piston is in position to strike, the valve directs flow into a chamber which drives the piston down. To assist in the working stroke, a hydraulic or a gas accumulator can be used. The hydraulic accumulator is charged on the return stroke. The hydraulic accumulator is released in the working stroke to support flow required by the fast-moving piston. The gas accumulator is charged on the return stroke as well. The piston compresses the gas into a high-pressure state. The energy in the compressed gas is used to accelerate the piston in the working stroke. The piston may also restore energy from the impact, if not all the energy was not transferred to the target. (Kim 2010) There are also differences in the high-pressure line when it is connected to the chambers. High pressure can alternate between the two chambers or it can be kept on either side. These are chosen design variables which lead to similar results. The valve directing the high-pressure line is controlled by the piston position, which leads to a high reciprocating motion when hydraulic power is supplied to the hammer.

The efficiency of the hydraulic hammer can be measured by comparing the hydraulic input power and the output power of the hammer. The impact energy is the kinetic energy of the piston at the moment of impact which can be calculated:

$$E_{\mathrm{p}} = \frac{1}{2} m_{\mathrm{p}} v_{\mathrm{p}}^2 \tag{4}$$

where, E_{p} is piston kinetic energy at moment of impact [J],
m_{p} is piston mass [kg] and
v_{p} is piston velocity at moment of impact [m/s].

Losses occur in the conversion of energy from the piston to the tool and hydraulic losses in the hammer. Therefore, the impact energy of the tool is lower than the impact energy of the piston. The energy content of the first stress wave in the tool is the impact energy in the tool. A guide to measure the impact energy of the tool has been developed by the Mounted Breaker Manufacturers Bureau of the Association of Equipment Manufacturers. With the impact energy measured, the total output efficiency of the hammer can be calculated as follows:

$$\eta_{\mathrm{tot}} = \frac{E \cdot f}{(p_S - p_R) \cdot Q} \tag{5}$$

where, η_{tot} is the total output efficiency of the hammer,
E is the output energy of the hammer [J],
f is the blow frequency [1/s],
p_{S} is the supply pressure of the hammer [Pa],
p_{R} is the return line pressure of the hammer [Pa] and
Q is the supply flow rate of the hammer [m^3/s].

According to measurements conducted using this method, the typical efficiency of a hydraulic hammer is approximately 70 %. Losses in the hammer consist of internal leakage, heat and sound losses.

The efficiency of hammering work is also affected by the material being hammered. Different materials require different impact forces. Hard materials require a larger impact force to break than softer materials. When higher impact frequency and lower impact energy is used for soft materials, and lower impact frequency and higher impact energy is used for hard materials, the efficiency of hammering work increases. The issue is controlling the stroke length during operation. Most hammers have a constant stroke length that results in constant blow energy and a decrease in efficiency, depending on the material. Some hammers have a manual option to change between a long stroke and a short stroke, but this is not an optimal solution. Mechanical automatic hard- or soft-mode operation has been developed but it involves complicated hydraulics in addition to the original hammer hydraulics. Yoon et al. (2019) propose a novel structure of a hydraulic hammer that automatically changes the stroke length depending on the material hammered. Proximity sensors are used to analyze the depth of the piston and a solenoid valve is used to control the displacement of the stroke. A 7 % increase in efficiency, from 50 % to 57 %, of the test system was measured and field tests gave promise for the technology. (Yoon 2019)

3.2 Electrohydraulic actuator

To minimize losses related to valve resistance, actuators controlled directly by pump flow have been developed (Inderlest 2020). Pump-controlled hydraulic systems are common in industrial use with less restriction in mass, machine size, and the ability. An example would be a hydraulic press constantly connected to a stationary grid. Mobile machinery has more strict requirements concerning safety, power density and energy efficiency. The limited space in the carrier requires small components. A mobile machine operated by a human close to bystanders makes safety difficult to achieve. Off-road machinery, such as excavators, can work in remote locations with no ready infrastructure. These factors lead to challenges in creating a pump-controlled actuator. (Inderlest 2020)

Zonal or decentralized hydraulics are being studied to improve the efficiency of an excavator. Studies by Niraula et al. (2018), Koitto et al. (2019) and Palavicino et al. (2020) discuss the development and efficiency of zonal and direct drive systems. The zonal hydraulics aim to eliminate valve-controlled systems and bring the hydraulic power source close to the actuator. Each actuator has its individual pump and motor to control the flow. The cylinders in an excavator experience high fluctuating loads and variable speeds. This makes it challenging to make it safe and have the optimal features. The responsiveness of the cylinders, for example, is a crucial feature for the operator.

Direct driven hydraulics have been suggested for the cylinders and the travel and swing motions of the excavator. The attachments have not been discussed in public research concerning direct driven hydraulics. The hydraulic hammer requires constant flow at a moderate pressure level. The loads do not change frequently during operation. The electrohydraulic power pack could support constant or variable speed or displacement. Different configurations include a constant or variable speed electric motor with a constant or variable displacement pump (Inderelst 2020). A variable permanent magnet motor can be designed with an efficiency of over 95 % (Palavicino 2020). A variable speed motor with a variable displacement pump allows for high control. The flow control desired for a hydraulic hammer is not very dynamic. A constant displacement pump controlled by the variable speed motor should be adequate.

3.3 Electromagnetic linear machine

The conversion of electrical energy directly to mechanical energy would be an option to improve efficiency. The conversion would eliminate energy conversions made in hydraulic power. The technology development in recent years has enabled the use of linear motors in new applications. There are three main types of linear motors: permanent magnet linear motor (PMLM), induction linear motor (ILM), and switched reluctance linear motor (SRLM). The theory, development and working principles of linear motors will be discussed in this chapter. In addition, the compatibility of use in an impact device such as a hammer will be considered.

The first linear motors were already invented in the 1800's. (Chowdhury 2017) The rapid development of electronics and material processing has led to an increase in the development of the linear motor. The linear motor differs from a rotary motor in that it produces a linear motion instead of a rotary motion. Linear motors can be thought of as rotary motors that have been cut off radially and flattened.

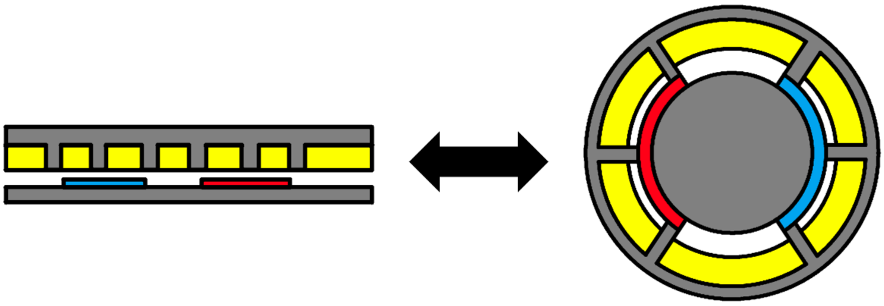

Figure 8. Transforming a rotary to a linear motor

Linear motion has been produced mainly by using rotary motors and converting the rotary motion to linear motion with, for example, sheaves, cranks or gears. Linear motors allow the producing of linear motion directly, with no mechanical links.

Every type of rotary motor has a linear motor counterpart. These types are permanent magnet linear motor (PMLM), induction linear motor and switched reluctance linear motor. The main difference between the motors is the excitation approach. The different machine types have their own advantages and disadvantages. (Lenin 2016) In addition to the types, there are different topologies in which the motors can be arranged. Different topologies include, for example, single-sided, dual-sided, tubular and flat. The selection of the topology depends on the application. The flat single-sided topology can be seen in the conversion of the rotary motor to a linear motor. It has a stator that drives the mover in a linear motion on the face of the stator. Adding a second stator on the other side of the mover makes a double-sided motor. A tubular linear motor has the stator or mover rolled around its length, making a tubular motor with movement either outside or inside. Tubular motors have an advantage in a higher force per volume ratio. This is a product of the normal forces between the stator and the mover being neutralized. (Bianchi 2002) The flat construction may have an advantage in the easier implementation of the entire magnetic core, resulting in reduction of core losses. (Bianchi 2002) The permanent magnet type linear motor has the highest capability to produce the required force in the hammer. The PMLM with a tubular topology provides the highest forces at the moment. This could be utilized in a hammer.

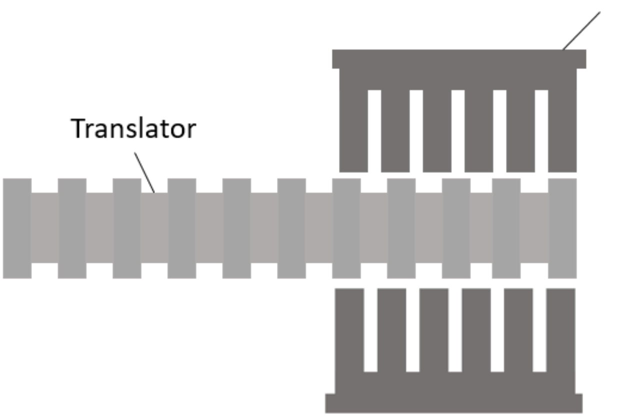

Figure 9. Double sided linear motor

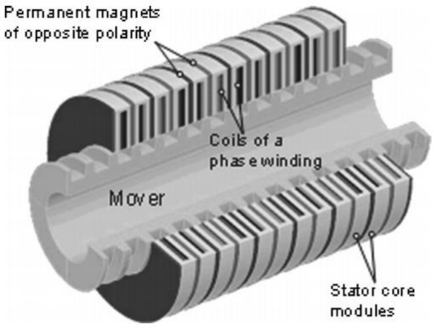

Figure 10. Tubular linear motor (Wang 2008)

Despite linear motors being similar to their rotary counterparts, they have the simple difference of having a beginning and an end in direction of motion. The motor is moving back and forth at various speeds which affect the performance. (Boldea 2018) This makes the design process of the linear motor more challenging and different. New characteristics, such as end effects, are formed at the beginning and end edges of the motor. End effects result in undesirable behaviors in the motor and have been under intense study in the last years. (Eguren 2019) The flux escaping from the ends of the machine results in the reduction of flux density in these regions. The asymmetry formed between the central and external poles of the motor complicates the control and analysis of them.

3.4 Electromechanical solutions

In electromechanical solutions, the reciprocating motion of the piston in the hammer is performed with a mechanical mechanism. An electrical supply power is utilized. In most cases, a rotary electric motor is used to convert the electrical energy into kinetic energy. The main issue is converting the rotary motion into the appropriate linear reciprocating motion of the piston. A crank mechanism is used in handheld tools to provide the impact energy on the tool. Clutch mechanisms could also provide a solution for making the reciprocating motion of the piston.

3.4.1 Crank mechanism

A crank mechanism is seen in handheld rotary hammers in the market. Research in different designs has led to the use of pneumatic impact mechanisms. Generally, they include an impact piston, which is connected to the drive by a pneumatic chamber. The two main mechanisms use either a moving piston or a moving cylinder. (Todorov et al 2010) Figure 11 shows a schematic of a moving piston, impact mechanism. The driving piston is connected to the crank mechanism with the connecting rod, producing the reciprocating motion. The movement of the driving piston results in compression and expansion of the gas volume in the gas chamber. The pressure difference from the variable gas pressure in the chamber drives the impacting piston to make cyclic impacts on the tool. The tool transfers the kinematic energy to the target being hammered in the form of a mechanical shockwave. In the moving cylinder type, the driving piston is replaced with a cylinder. The impact piston is placed in the cylinder, forming a gas chamber.

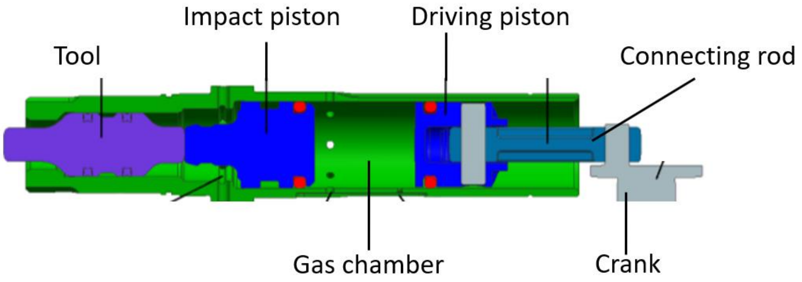

Figure 11. Schematic of the moving piston type impact mechanism (Yan et al. 2016)

The gas chamber acts as a spring between the impact piston and the driving piston or cylinder. In the stroking motion of the impact piston, the gas is compressed. The high gas pressure results in a pushing force until the impact piston has reached the maximum velocity. The typical speed of the impacting piston is between 8 m/s and 10 m/s (Todorov et al. 2010). After the impact, the gas pressure starts to decrease and the striking piston starts the return stroke. When the driving piston or cylinder reaches the top position, the moving impact piston compresses the gas and comes to a stop. The gas chamber acts as a spring, storing the kinematic energy of the return stroke of the impact piston. The stored energy is then used in the next stroking motion to accelerate the impact piston. The repeated energy transformation powered by the crank and connecting rod results in cyclical impact operation. (Yan et al. 2016)

The frequency of the impact is controlled by the rotational velocity of the crank mechanism. The dimensions of the gas chamber influence the reaction forces, which relate to the vibration in the handle of the tool. The vibrations are more crucial in handheld tools than machine-operated ones. The mass of the impact piston affects the impact energy of the machine. Handheld breakers are mainly used in the demolition of concrete due to impact energy levels. The largest machines have a range of 70-80 J of impact energy per blow (Patent no. US 2019 / 0232478 A1). This is significantly less than the smallest hydraulic hammers.

3.4.2 Clutch mechanism

A clutch mechanism could be used to transfer power from a rotating electric motor to a striking piston, to produce a cyclical impact sequence. The source would be coupled to the piston with gears or a friction wheel. The impact piston would be raised against a gas spring. The spring stores the energy in the compressed gas. The gas spring would provide the energy for the stroking motion. This mechanism relies on the clutch between the power source and the piston. The clutch engages cyclically to provide power for the return stroke of the piston. When the clutch disengages, the piston is free to perform the working stroke using the gas spring.

A challenge with this method is the frequency of clutch engagement. Typical hydraulic hammer frequencies are between 5 Hz and 30 Hz. This sets a requirement for the engagement time and frequency of the clutch. To reach the frequencies required by hydraulic hammers, the clutch would have to engage every 20 to 200 ms. This is a high requirement for a clutch, but there are examples of applications in the automotive industry which have solutions with fast clutch engagement. A dual clutch transmission is able to shift gears in 8 to 100 ms. The difference in this application is the switching frequency. Van de Ven and Cusak (2014) designed a digital pulse-width-modulated clutch. It utilizes a novel clutch design with a double dwell axial cam with a profile that varies with the radius.

Three translating followers are used to control the duty cycle. The clamping force for the clutch is created through deflection of the components and springs in series with the cam followers. This clutch design minimizes clutch slip during engagement and disengagement. The design was tested with a switching frequency of 22 Hz. Efficiency of the clutch in the experimental trials was 55 % due to clutch slip (Van de Ven and Cusak 2014). Using a similar friction clutch could result in higher efficiency in hammering if controlled properly. After the piston impacts the tool, the piston bounces upwards. This energy is stored in the gas spring but, if the clutch engagement is done during the bounce, slip could be minimized.

4 PRESENT STATE MEASUREMENTS OF HAMMERING

This chapter focuses on the measurements conducted for the thesis. The main objective was to measure the main power losses concerning hammering work using a hydraulic excavator. Understanding the power losses in the system gives important knowledge for methods to improve the efficiency of the machine. The setup of the equipment and the process of the measurements are explained. The results of the measurements are also presented.

4.1 Measurement system setup

The excavator used in the measurements was a CAT 305C CR (Figure 12). The operating weight of the machine is 5200 kg, so it is considered to be a mini excavator. The fact that the electric excavators produced at the moment are in the small-size range led to the choice of the CAT 305C CR. The excavator is equipped with a load sensing system, which represents the state-of-the-art technology used to improve efficiency. This machine was used for testing in the workshop of Sandvik Lahti site. For this reason, there were some modifications and additional options in the machine. These were disabled to simulate a machine used by a consumer. The excavator was operated by an experienced operator.

The hydraulic hammer attached to the excavator was chosen based on the carrier's weight. The hammer is compatible with carriers in the range of 1.9 to 8 tonnes. The oil flow range of the hammer is 35 to 90 l/min. The CAT 305C CR provides 70 l/min at 2400 RPM to the auxiliary line, which was appropriate for the hammer. The hammer is controlled by the operator with a switch, which opens the pump flow to the auxiliary circuit.

Figure 12. CAT 305C CR used in the measurements

Power losses occurring in the system mainly consist of pressure losses, as mentioned in the literature review. The oil flow of the system was also measured to calculate the total power. Pressure transducers and flow meters were positioned in different parts of the system. A flow meter and a pressure transducer were added in a line from the pump to the main control valve to provide accurate information of the supply power. A pressure transducer was placed on the auxiliary line output of the main control valve to measure the pressure loss in the main control valve. A pressure transducer and a flow meter were placed close to the hammer for the hammer input power. Pressure transducers were also placed in the boom, arm and bucket cylinders to determine the pressure levels the pump experiences from the front attachment. The load sensing line was equipped with a pressure transducer to determine the pressure signal the pump receives. Figure 13 illustrates the position of each sensor. The type of each sensor is in Table 1. The data was collected to a computer using an HBM signal amplifier and National Instruments voltage input module. A sampling frequency of 10 kS/s was used.

Table 1. Sensor locations and types

Hydraulic pump flow Q_p	Hydrotechnik RE4-600
Hammer flow Q_v	Kral OMG-32
Hydraulic pump output pressure p_p	Kyowa PGS-500KA
Hammer operating pressure p_k	Kyowa PGS-500KA
Main control valve auxiliary output pressure p_{aux}	Kyowa PGS-500KA
Load sensing pressure p_{ls}	Kyowa PGS-500KA
Boom cylinder rod pressure p_{1r}	Kyowa PGS-500KA
Boom cylinder piston pressure p_{1p}	Kyowa PGM-500KE
Arm cylinder rod pressure p_{2r}	Kyowa PGS-500KA
Arm cylinder piston pressure p_{2p}	Kyowa PGS-500KA
Bucket cylinder rod pressure p_{3r}	Kyowa PGS-500KA
Bucket cylinder piston pressure p_{3p}	Kyowa PGS-500KA

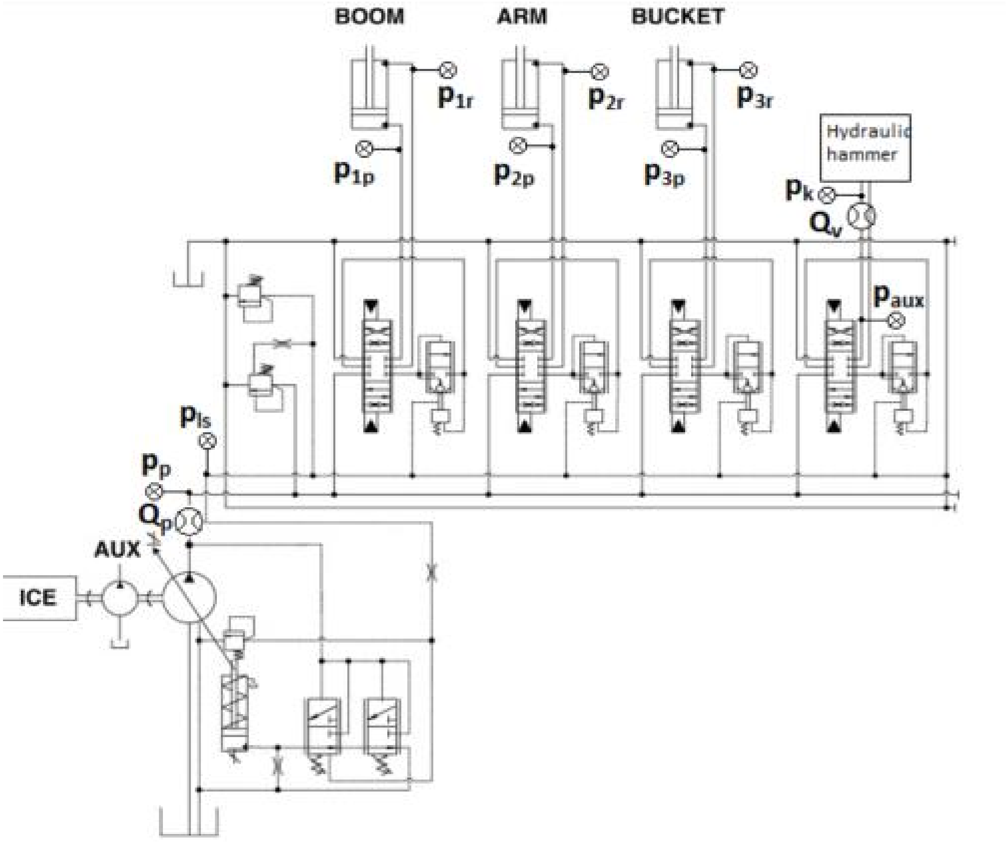

Figure 13. Simplified hydraulic schematic of the instrumented excavator

4.2 Measurements

The measurements were divided into three different parts. The first part consisted of measuring the power losses when using the auxiliary line only. In the second part, the pressure levels of each cylinder were measured while pressing the hammer down. The third part combined the two previous tests.

Hammer work is done by pressing down on a surface to apply the necessary preload and providing flow through the auxiliary port. By dividing the measurements into these parts allowed a clearer view of the losses in the system. There were also limitations on the number of sensors that could be used simultaneously. The number of channels was limited to 9. In addition, in the third part, not all cylinder pressure transducers were used. So, the second part was used to confirm which cylinders were necessary.

In the first part of the measurements, flow was provided to the auxiliary circuit only. This way, the losses caused by only running the hammer could be seen. The pump pressure, output pressure of the main control valve auxiliary, auxiliary line pressure and the pump flow were measured. Since the flow of the machine is determined by the motor speed, the flow was raised incrementally by raising the motor speed from the minimum to the maximum. The hammer was not connected in this measurement, so there was no restriction in the auxiliary line. As seen in Figure 14, at the maximum flow, the auxiliary line pressure loss was approximately 8 bar. This is mainly caused by the pressure from the hydraulic lines to the tank. The pressure at the main control valve output is slightly higher at 13 bar. This, as well, is mainly the pressure from the hydraulic lines. A large difference in pressure can be seen between the pressure at the hydraulic pump and the output of the main control valve. With the pressure at the pump being 43 bar, the pressure difference caused by the main control valve is 30 bar. This means the hydraulic motor must provide 5.4 kW of hydraulic power to the system with no external loads at full flow capacity. The hydraulic power at the auxiliary line is 1 kW, which means the power loss between the pump and the auxiliary line is 4.4 kW. The same measurements were also conducted with a pressure of 110 bar in the auxiliary line at maximum flow. The power loss between the pump and the auxiliary line was similar to the previous at 4.7 kW.

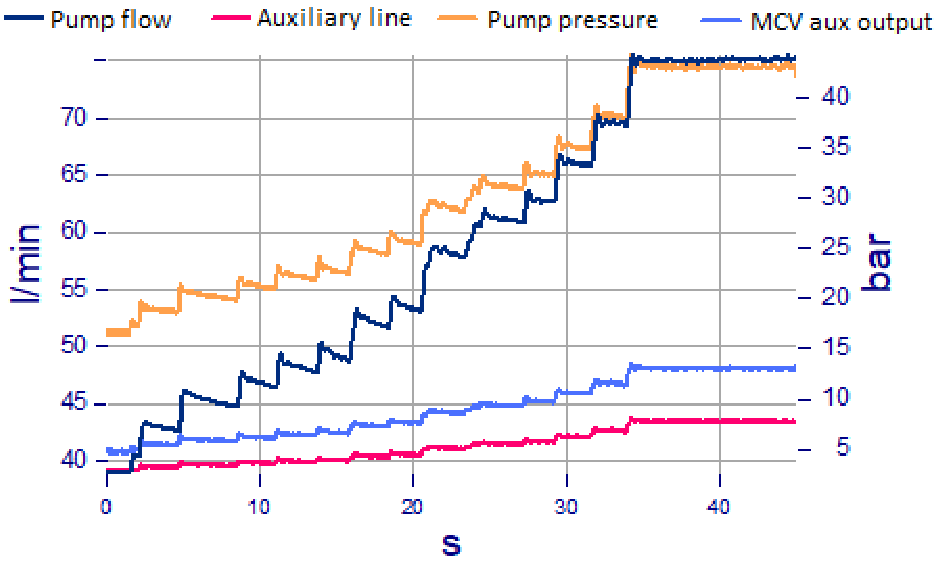

Figure 14. Pressure and flow data

The second group of measurements focused on the effect of the boom movement while hammering. The main objective of these measurements was to see if the pressure in the cylinders exceed the hammer's pressure level. The pressure on both sides of the cylinders in the boom, bucket and arm were measured. The pressure and flow of the pump and the load sensing line were also included. Measuring the pressure in the cylinders while applying the appropriate preload in hammer work gives information about the pressure level of the front attachment. The motor speed was set to 2000 rpm for the measurements. This is a typical working speed for the machine and it provides enough power for hammering work.

The preload was applied at three distances from the excavator to the ground. The locations were 1) close to the excavator, 2) at an optimum working distance, and 3) with the front attachment extended out. The way which the operator controls the front attachment to apply the preload may vary. For this reason, the preload was applied in two ways, by using the boom cylinder only and by compensating with the use of all the cylinders. It is also possible for the angle of the hammer to change during the preload. In the situations where the preload is applied with the boom cylinder only, the pressure in the rod side of the boom cylinder reaches the pump's maximum pressure of 245 bar. This means that the pump experiences the 245-bar pressure when the boom is controlled by the operator. The pressure remains in the cylinder until the preload is relieved. The pump only needs to provide power to the cylinder when the cylinder is controlled with the joystick. The pump pressure, using multiple cylinders to apply the preload and to adjust the hammer orientation, can be seen in Figure 15. The pressure peaks caused by the arm and the stick cylinders reached pressure peaks of 160 bar to 245 bar. The highest pressures affecting the pump appeared in the bucket cylinder and the boom cylinder.

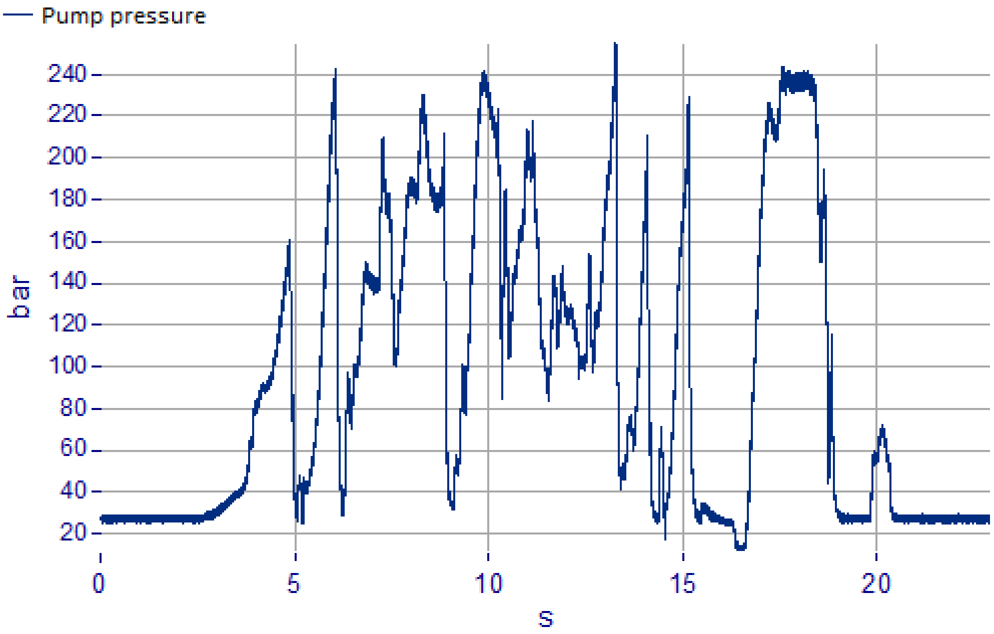

Figure 15. Hydraulic pump pressure when applying preload

The final part of the measurements consisted of applying the preload while using the hammer. The hammer was pressed against a concrete surface. While hammering the concrete, the cylinders were controlled as in the second part of the measurements. As seen in Figure 16, the pressure of the pump rose to the boom cylinder pressure of 245 bar when the initial preload was applied. The operator maintained the preload by actively controlling the boom cylinder with the joystick. A pressure of approximately 215 bar was at the pump while the active preload was applied. After the initial preload, the hammer was supplied with flow. The pressure fluctuation of the hammer was high, varying from 50 to 140 bar, with the average being approximately 105 bar. When the preload was not actively controlled, the pump supplied power to the hammer only. The pump pressure decreased down to approximately 133 bar. The flow remained fairly constant at 46 lpm when the preload was actively applied. Fluctuation occurred in the flow when the pressure level of the pump changed. Relieving the active preload raised the pump flow momentarily and applying the force lowered the flow momentarily. Because the movement of the cylinder is small, majority of the flow provided by the pump was consumed by the hammer. Using multiple cylinders to apply the preload resulted in similar rises in pressure to around 200 bar.

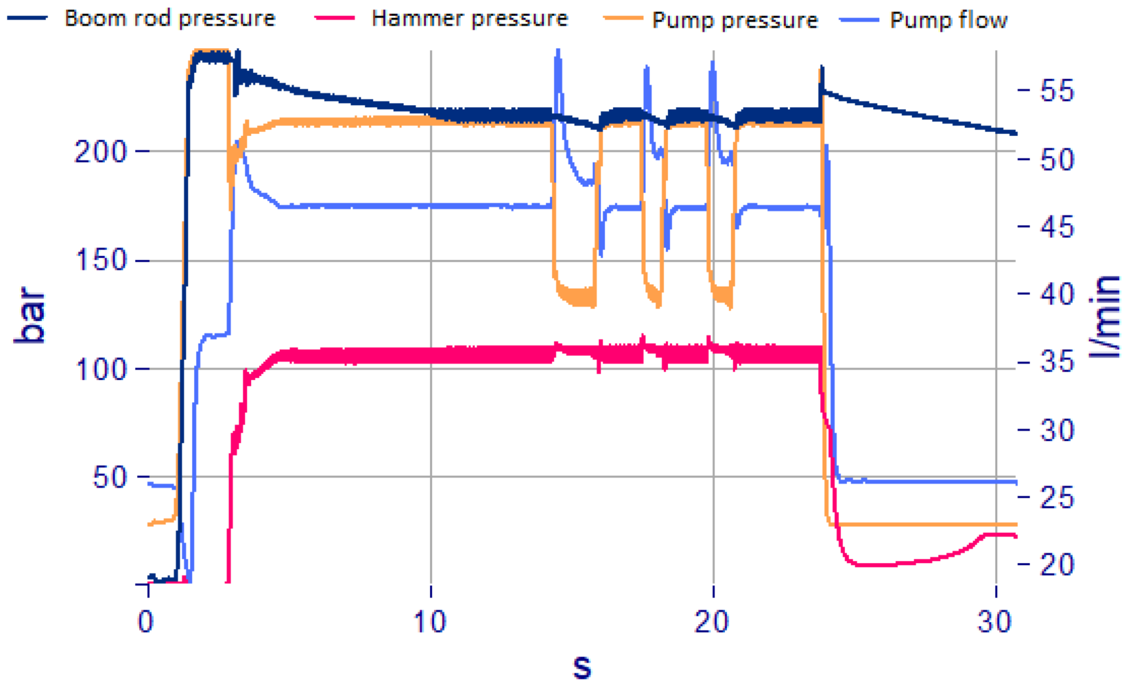

Figure 16. Pressure and flow

The hydraulic power of the pump and hammer can be seen in Figure 17. The hydraulic power remained stable at constant preload. A fluctuation in power was caused by a drop in pump pressure, which momentarily increased the flow rate. The hydraulic power of the motor while actively applying the preload was 16.5 kW. It was 9 kW higher than the hammer's hydraulic power at 7.5 kW. The hammer used only 45 % of the power supplied by the pump. The large difference in power was due to the pressure difference between the hammer and cylinder. The pump must supply the hammer with constant high flow, while the pressure level of the pump is determined by the hydraulic cylinder. The flow required by the cylinder was not measured, so the cylinder power could not be calculated. However, very little movement of the boom cylinder was observed during the measurement. Also, when comparing the flow at the hammer to the flow at the pump, the difference in flow can be calculated. Supplying power to the hammer only showed a 9 % decrease in flow between the pump and hammer. Simultaneous use of both the hammer and the cylinder showed roughly a 7 % decrease in flow between the pump and hammer. These suggest the flow required by the cylinder during the active preload is small. Therefore, the majority of the power provided by the pump were losses.

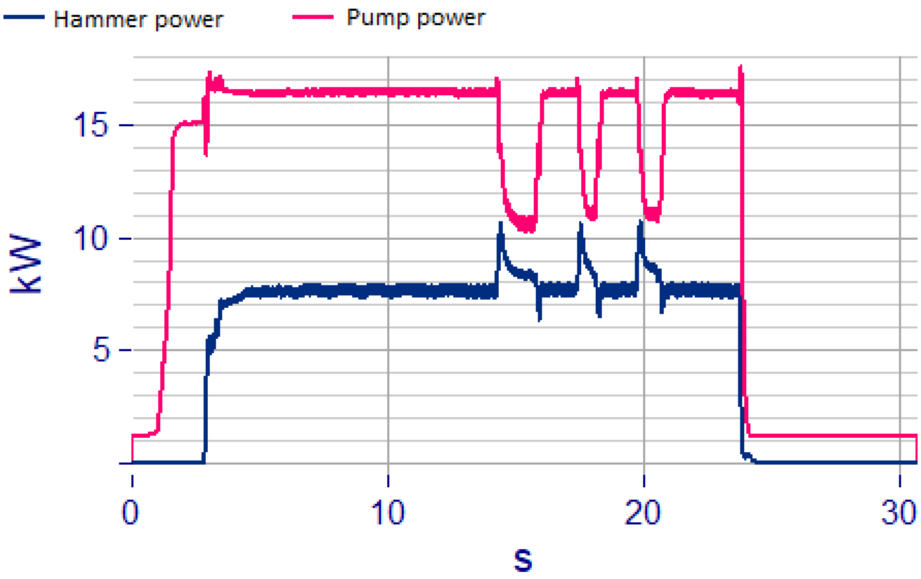

Figure 17. Pump and hammer hydraulic power

When the hammer was the only actuator used, the output power of the pump was 12 kW and the input hydraulic power to the hammer was 9 kW. This resulted in a 25 % drop in power between the pump and the hammer. Due to the pulsation caused by the hammer in the hydraulic line, the hydraulic line losses could not be separated from the measurements. To determine the distribution of the loss, the hammer was replaced with a throttling valve. The flow to the auxiliary line was supplied and the pressure was set to the hammers working pressure. From this measurement, the hydraulic line resulted in a 3 % power loss and the main control valve, 22 %.

5 ELECTRIC HAMMER CONCEPTS

The aim of this chapter is to evaluate four concepts for hammering using the technology described in the literature review. The four concepts are the electrohydraulically powered hammer, linear machine hammer, pneumatic-electromechanical hammer and electromechanical hammer. The concepts consist of currently researched technology for hammering, as well as novel methods which have not been publicly researched for hammering. Quantitative and qualitative properties of the concepts are reviewed. The quantitative properties include the energy efficiencies of the machines. The main components of each machine are described and the overall energy efficiency is examined. Simple calculations are made to estimate the output energy of the hydraulic hammer. This is used for calculating properties of the concepts. For the quantitative comparison of the concepts, a baseline has to be established. This consists of an electric motor-powered hydraulic excavator using a hydraulic hammer. All the concepts are assumed to be used with a similar electric excavator. The qualitative comparison includes properties which cannot be measured. The qualitative properties include technical maturity, reliability, size, controllability and maintenance. By taking the qualitative properties into account with the energy efficiencies, an overall view of the concepts can be made.

5.1 Conventional hydraulic hammer as a baseline

The baseline is established in this chapter. This consists of an electric motor-powered hydraulic excavator using a hydraulic hammer. The power source provides the energy for the electric motor to run the hydraulics of the machine. The components of the power chain are shown in Table 2. The efficiency of each component is estimated, and the overall efficiency is calculated. Since the power source is the same in every concept, it will not be included in the power chain. The least efficient component is the hydraulic hammer at 70 %. The rest of the losses are due to the excavator system. Using the measurements in Chapter 5 and studies by An et al. (2020) and Bedotti et al. (2017), the efficiencies of the hydraulic system are defined. A major part of the losses come from the main control valve. In a digging cycle, An et al. (2020) state that the efficiency of the valve is 78.4 % and Bedotti et al. (2017) states a similar 77.3 %. Considering that the digging cycle is different from a typical hammering cycle with respect to how much simultaneous cylinder use there is, the efficiency of the main control valve may be higher. Considering these studies and the measurements done for this work, the efficiency was set to 80 % for the main control valve. The hydraulic line efficiency was also determined with the same studies and measurements as the main control valve. Since the pump efficiency could not be measured in this work, it was estimated to be 80 % using the studies mentioned above. The electric motor requires electrical lines and an inverter. In a study by Burt et al. (2008), the efficiency of an inverter was measured. The efficiency was dependent on the load factor but was found to be no less than 95 % at any time. The electrical line losses are very minimal due to the relatively short cable lengths. These are still taken into account with an efficiency of 99 % (1997). The electric motor efficiency can also vary depending on the load. Assuming the system was designed to work in the normal working range, an efficiency of 90 % was chosen (Tianliang 2021). The overall efficiency of the conventional hammer system comes to 36 %.

Table 2. Conventional hammer power flow

Power flow	Efficiency
Hydraulic hammer	70 %
Hydraulic lines	95 %
Main control valve	80 %
Hydraulic pump	80 %
Electric motor	90 %
Inverter	95 %
Electrical line	99 %
Total efficiency	36 %

5.2 Electrohydraulically powered hammer

The electrohydraulically powered hammer is the closest concept to the existing hammering setup. This option utilizes the existing hydraulic hammer with a construction machine. The difference to a conventional setup is that the hydraulic power is provided by a separate pump, which is powered by an electric motor. The main objective is to minimize the losses formed in the hydraulic system of the excavator, as described in Chapter 2 and seen in the measurements described in Chapter 5. Compared to the conventional hammer and excavator, this structure improves the energy efficiency by cutting the main control valve out of the energy flow and utilizing the hydraulic pump more efficiently. The components in the system energy flow were determined and the energy efficiency can be seen in Table 3. In Figure 18, a chart of the layout is presented When using a fixed displacement pump with a variable speed control, the pump efficiency can be raised to 90 % (Tianling 2021). With the lack of a main control valve and the pump improvement, the overall efficiency comes to 51 %. This means an increase of 15 percentage points in efficiency compared to the conventional system. This is a notable change in efficiency, but the main restriction to improvement is in the multiple transformation of energy from electric to hydraulic to mechanical.

Table 3. Power flow and efficiency of the electrohydraulically powered hammer

Power flow	Efficiency
Hydraulic hammer	70 %
Hydraulic lines	95 %
Hydraulic pump	90 %
Electric motor	90 %
Inverter	95 %
Electrical lines	99 %
Total efficiency	51 %

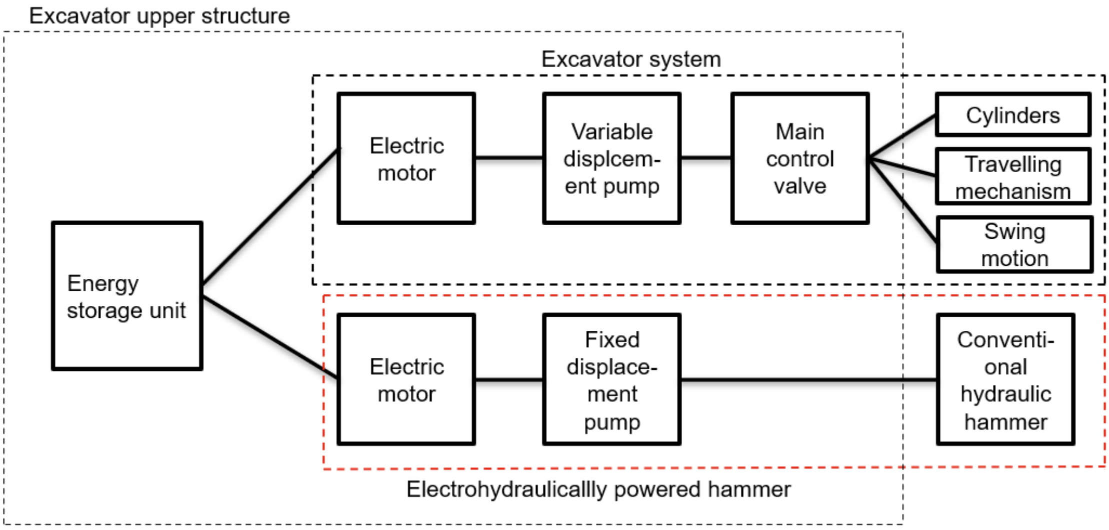

Figure 18. Chart of the electrohydraulically powered hammer

The electrohydraulically powered hammer consists of components that are well known and researched. The hammer is a conventional hydraulic hammer, but it is powered by a different source. The power source, which consists of an electric motor and a fixed displacement pump, are common components of hydraulic systems. This means the well-known components are utilized in a new way. The maturity level of this concept is fairly high compared to the alternative novel structures. Other applications are found in studies using a motor-controlled pump to improve the efficiency of the system.

The system includes additional components compared to the conventional hammer. Adding an electric motor and a pump requires installation space and increases weight. Locating the new components in the hammer is not feasible. The additional weight in the attachment would increase the load on the cylinders of the front hoe and increase the excavator's energy consumption. It would also make the hammer bulkier and less easy to work with. The logical place for the power source would be in the excavator. This also avoids extra electrical lines having to be routed in the front attachment. But adding components to existing excavators can be problematic. The excavator would have to be modified to fit the power source when purchasing the hammer. The trend of minimizing the weight and size of excavators would become an issue. A requirement to modify the excavator when purchasing a hammer could also affect users with occasional needs for a hammer. The location of the power source would need collaboration between the attachment companies and the excavator manufacturers.

The scalability of this concept through the hammer sizes ties in with the size of the power source. While smaller hammers need smaller power sources, the trend of small range excavators is a concern. The need to minimize the size of the excavator to fit small work sites and to be able to maneuver in the streets makes it difficult to add components to the excavator. Also, the trend of electrification is starting in the smaller range and the need for a more energy efficient hammer would be there first. As the hammer size grows, the power source grows as well. On the other hand, the machines using larger hammers have different requirements for size and a different work type in most cases. The larger machines are used in construction or mining sites which do not limit the moving space and the travel distance is often not an issue. The size of the machine is therefore not as critical as in the smaller range. This presents an opportunity to find the space for the power source. The use of these excavators is typically more focused on demolition and, in some cases, requires using only a hammer. This could incentivize the user to invest in the modification of the machine for improvement in total efficiency. The electrification of the larger size machines must be considered as well. With the trend starting from the smaller range, the need for a larger electric hammer will trail behind the smaller range.

While this concept brings a fairly simple improvement to the efficiency, other properties see no clear improvement. The ability to increase the controllability of the hammer is low in the electrohydraulic hammer. Only the flow from the hydraulic power source can be adjusted. This can also be done with the conventional system today. Other drawbacks might include safety factors and maintenance of the machine. The addition of high voltage electronics brings more complexity to the pure mechanical structure of the hammer system of today. On the other hand, the electric excavator will most likely include similar components as the power source. This means the infrastructure and the readiness to deal with the high voltage electronics that are included in the power source will not be a major concern.

5.3 Linear machine hammer

The linear machine hammer differs from the conventional hammer significantly. Transforming the electrical energy directly into mechanical energy makes the linear machine viable for a more energy efficient hammer. A visualization of the main components is presented in Figure 19. The flow of energy, which can be seen in Table 4, is the shortest of all the concepts. The main losses in the system are from the electromagnetic losses in the linear machine and the gas spring. Multiple studies refer to the high efficiency as a property of linear machines, but give no specific values. The majority of the research is still focused on the topologies and attaining the needed force and speed properties. Studies by Xu et al. (2019) and Hu et al. (2020) research a permanent magnet linear generator applied to a free-piston engine. They state the efficiency of the machine from mechanical to electrical energy to be from 80 % to up to 95 %. Lu et al. (2015) and Abbas et al. (2008) give an efficiency of 70 % to 90 % for a permanent magnet linear machine. The efficiency of the machine depends on parameters that will have to be chosen in the design phase of the machine. For this work, an efficiency of 80 % was chosen for the linear motor, based on the studies mentioned. The addition of a gas spring in the system is to reduce the force required from the linear machine. Losses in the gas spring come from heat loss and leakage, but they are minimal. The losses are minimal and an efficiency of 90 % is used. Electrical losses from the electrical lines and the control unit are similar to the rotary counterpart. The total efficiency of the linear machine comes to 68 %. The more direct flow of energy shows in the 32 percentage point change in efficiency compared to the conventional hammer.

Table 4. Power flow and efficiency of the linear machine hammer

Power flow	Efficiency
Linear motor	80 %
Gas accumulator	90 %
Electrical line	99 %
Control unit	95 %
Total efficiency	68 %

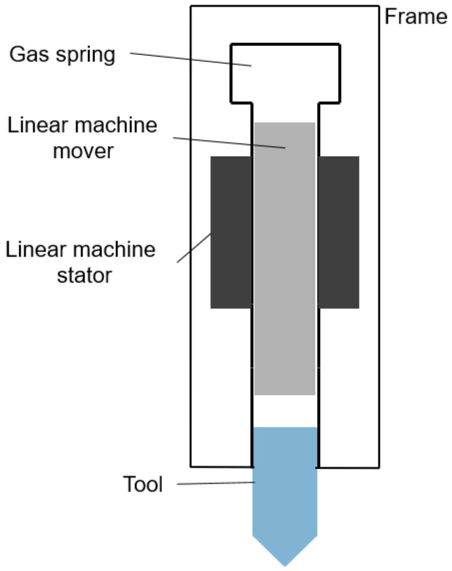

Figure 19. Linear machine hammer concept visualization

Technical maturity enters the discussion with the more novel concepts such as the linear machine. Linear machines, in particular, are not brand-new technology. They have larger applications in the transportation industry and launch technology, but they also have smaller applications in cooling technology and in replacing hydraulic and pneumatic cylinders. The force and speed requirements for these applications differ from the ones needed in a hammer. High speed reciprocating motion, with enough force to accelerate a mass to exert enough energy for breaking material, is not seen in use. Research is being made in this field with hammers and machines with properties similar to the linear piston machine, but the level is currently mostly experimental.

The reliability of this concept remains a prominent issue. The hammer contains large amounts of electronics and magnetic materials. The nature of the hammer causes high vibrations in the components. The damping of the vibrations must be solved for the electronic parts included in the hammer. The magnetic material in the mover is exposed to the high impact when the mover hits the tool. The properties of the permanent magnet can change in high impact and eventually lose the magnetization. The linear machine is also susceptible to contamination. Hammers are used in rough environments, with the constant presence and formation of dust. The machine must be enclosed so the permanent magnets cannot be contaminated. While the cooling of the machine is already an issue with the lack of hydraulic fluid, the protection from contamination can exacerbate the heat issue.

A clear advantage in the linear machine is the controllability of the blow. Control of the position and speed of the mover means the energy of every blow and the frequency of the hammer can be adjusted. Since the optimal blow energy depends on the material being hammered, the high control gives advantages on the overall productivity. The higher efficiency of the breaking operation improves the overall efficiency of the machine. Higher controllability will also give more options for automation. When single blows can be controlled, it is possible to adjust the blow energy according to the properties of the target within a single blow series and raise the efficiency and productivity.

The electronics bring a new component to the maintenance of the machine. The high voltage lines require a different skill set for maintenance and safety. The hammer mechanism being controlled by electronics will also affect the maintenance. The high controllability comes with more complex electronics that have not been seen in the attachment industry. The infrastructure for technical support and maintenance must be made. On the mechanical side, the linear machine brings an interesting feature. While the controls and electronics are complex, the structure of the machine is simple. The mover and the tool are the only moving parts in the machine. The contactless mover requires no lubrication and has little wear. This gives the linear machine the reputation of being a low-maintenance or maintenance-free machine.

5.4 Pneumatic-electromechanical hammer

The pneumatic-electromechanical hammer is another electric hammer concept. The use of a rotary electric motor instead of linear one adds a component to the energy flow. Rotary motion from the electric motor is transformed into linear motion with a crank mechanism. The concept is shown in Figure 20. Between the motor and the crank, a transmission is used with an efficiency of 98 %. The mechanism includes a pneumatic link which couples the crank mechanism and striking piston. The pneumatic link acts as a gas spring to increase the velocity of the piston, but also dampens the peak torques from the electric motor. If designed properly, the gas spring should work with minimal losses. An efficiency of 90 % was chosen for the pneumatic link. The electrical losses are considered the same as in the electrohydraulically powered concept. Overall efficiency of this concept is calculated to be 75 %. This is a 39 percentage point increase compared to the conventional hammer.

Table 5. Power flow and efficiency of the pneumatic-electromechanical hammer

Power flow	Efficiency
Pneumatic link	90 %
Transmission	98 %
Electric motor	90 %
Electrical line	99 %
Control unit	95 %
Total efficiency	75 %

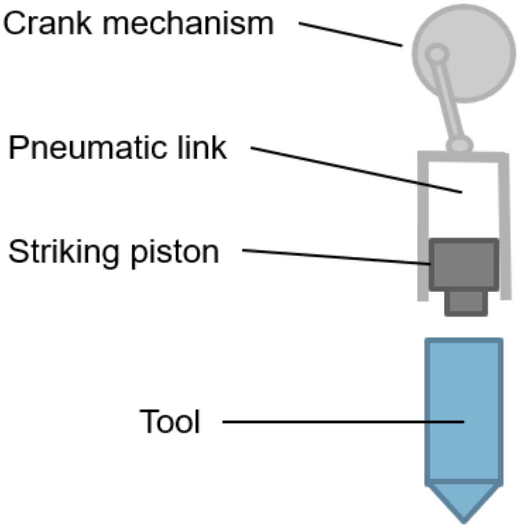

Figure 20. Pneumatic-electromechanical hammer concept visualization

The technical maturity of this concept is moderate due to its use in handheld machines. The same mechanism is used in large handheld jackhammers. These machines are close in size to the smallest hydraulic hammers but do not reach the same impact energy. The main components of the hammer include the electric motor and crank mechanism. These can be considered as matured technology. The fact that the mechanism is proven in commercial handheld products gives a strong advantage for implementation in larger machine sizes.

The technological advances in electric motors have made it possible for electromechanical hammers to reach their hydraulic and pneumatic counterparts in power. The compact electric motor has high enough performance to power the tool. While the handheld hammer is compact, it is close to the dimensions of a small hydraulic hammer. This is partly due to the ergonomics, which means that the design of a pneumatic-electromechanical hammer for machines would be more free, considering the layout of the hammer. There would still be restrictions in height because the crank mechanism must be located above the striking piston. The power density of the motor is an important factor. The range of the output power is large in hammers. Values from 4 kW to over 100 kW are seen in hydraulic hammers. This presents an issue in the motor size. The mass and the dimension grow as the power of the motor increases. In the small range, the motor size could remain manageable. In larger range, the weight and size could be a challenge.

The pneumatic-electromechanical hammer mechanism restricts the controllability of the machine. The electric motor speed can be controlled but the restraining features are in the crank mechanism. The crank radius is responsible for the speed and the stroke length of the impact piston. If the frequency of the hammer is adjusted by only reducing motor speed, the impact energy will decrease due to a decrease in piston velocity. With the velocity being constant, the stroke length does not directly affect the final impact speed as in the hydraulic and linear machine hammer. To improve the controllability of this concept, the crank radius would have to be adjustable. Together with the motor speed and adjustable crank radius, the frequency and the impact energy could be controlled. The dynamics of the pneumatic link could suffer from a variable crank radius. Another factor in the control is when the motor is fixed to the crank mechanism; starting and stopping the hammer requires the motor to stop and start. This means a delay in the time from when the operator is ready to hammer to when the motor has reached the desired speed. Considering that this is almost instantaneous in both the hydraulic and linear machine hammer, the delay becomes a factor. The nature of hammering work consists of multiple short cycles, and even a one second delay may affect the work and the operator.

5.5 Electromechanical hammer

The electromechanical hammer concept was chosen as the fourth concept. In this concept, the hammer is powered with a rotary electric motor but the power is mechanically linked rather than pneumatically linked as in the previous concept. The piston is driven against a gas spring which drives the working stroke of the hammer. A visualization of the concept is shown in Figure 21. As with the linear motor concept, the gas spring efficiency was chosen to be 90 %. A large issue in this concept is the transmission of power from the rotary to linear piston movement in short cycles. A friction clutch transmitting the power of the electric motor to the piston was chosen. A friction wheel connecting the driving axle to the piston produces the needed return stroke to compress the gas spring. The efficiency of the friction clutch is hard to estimate. A high-speed engagement clutch designed by Van de Ven and Cusack (2014) had similar properties needed in a hydraulic hammer. The largest factor affecting the efficiency of the clutch was the slippage. Van de Ven and Cusack (2014) determined the disc clutch efficiency to be 55 %. With a design of the clutch for the hammer properties and duty cycles, the efficiency could be significantly higher. For example, the timing is crucial for energy efficiency. Adding up all of the components (Table 6), the total efficiency is estimated to 41 %. This is in the same range as the hydraulic hammer. The most significant component affecting the efficiency is the clutch.

Table 6. Power flow and efficiency of the electromechanical hammer

Power flow	Efficiency
Electrical line	99 %
Electric motor	90 %
Transmission	98 %
Gas accumulator	90 %
Control unit	95 %
Clutch	55 %
Total efficiency	41 %

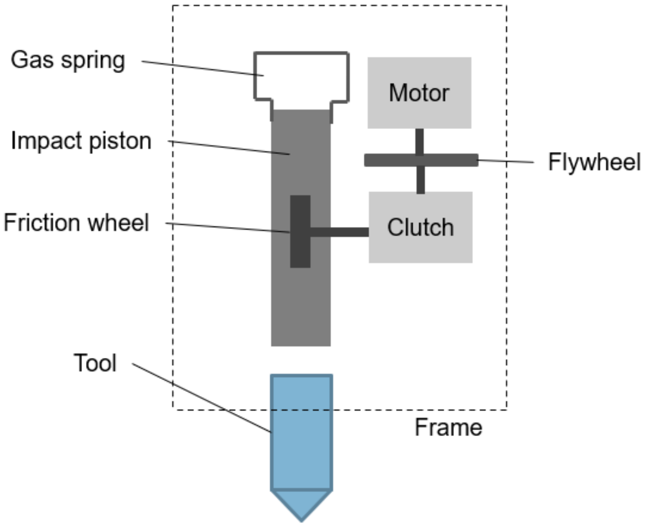

Figure 21. Electromechanical hammer concept visualization

The components of the electromechanical hammer are well known but the control requirements are new. This makes the mechanism immature compared to the hydraulic hammer. A novel clutch mechanism would need to be designed to fulfill the requirements for hammering.

The size and scalability face similar issues to the pneumatic-electromechanical hammer. The motors, being in the hammer itself, grow as the need for power increases. Utilizing a flywheel to compensate for the fluctuating power adds components to the hammer. Fitting the components in the hammer is a challenge. The weight also increases with the added components. Controlling the impact energy is feasible with increased complexity.

6 RESULTS AND DISCUSSION

The objective of the measurements was to find the main sources of power loss in the hydraulic system of the carrier during hammering work. Similar studies on hydraulic excavators with load sensing systems have been conducted for digging cycles, but not for hammering (Zimmerman 2007; Vukovic 2017; Casoli 2020). A typical hammering cycle has not been determined and creating a hammering cycle did not fit the scope of this thesis. Therefore, the functions performed in hammering work were analyzed individually.

While providing power only for the hammer, a 25 % loss in hydraulic power was measured between the pump and the hammer. The losses are a result of the pressure drop in the main control valve and hydraulic lines. The majority of the losses occur in the main control valve, causing a 22 % loss of the pump output power. This is considered an ideal situation for the load sensing system because there is only one actuator being controlled.

The other function performed in hammering is providing the preload on the hammer. Applying the preload using the front attachment results in high pressures in the cylinders. The pressure level of the cylinders depends on the way the preload is applied. A peak pressure of 180 to 245 bar can occur in the cylinders during the preload. These values were considerably higher than the 105-bar working pressure of the hammer. If the preload is actively applied when the hammer is operated, the pressure difference between the cylinder and the hammer is significant. The system pressure needs adapt to the high pressure and also provide high flow to the hammer. This leads to high power demand from the pump. The pressure of the pump must be reduced for the hammer, which leads to additional throttling losses in the main control valve. In this situation, the boom cylinder and hammer were controlled simultaneously; the hammer input power was 45 % of the power provided by the pump. The remaining 65 % included the losses, but also the hydraulic power of the boom cylinder. The flow to the cylinder was not measured. However, using the difference of the pump flow and hammer flow, a maximum flow could be estimated for the cylinder. In this case, the power of the cylinder was 6 % of the pump output power. This means 49 % of the pump output power is consumed by the throttling losses in the main control valve and hydraulic lines. This is a similar result to what Zimmerman et al. (2007) measured in a load sensing excavator using multiple actuators. Vukovic et al. (2017) stated that approximately half of the pump output energy is lost through throttling in the valve and other hydraulic losses, such as friction loss in pipes. This corresponds with the measurement using the hammer and the boom cylinder simultaneously.

The entire hydraulic system was not measured in this thesis. The output of the hydraulic pump was measured but the input energy could not be measured. Using the mechanical input energy, the efficiency of the hydraulic pump could have been calculated. In the literature review, the efficiency of the pump was from 60 % to 90 %, depending on the displacement and pressure of the system. In hammering, these values can reach higher values more consistently than a digging cycle, which could lead to higher efficiency in the pump.

To find the energy efficiency of hammering work, a work cycle would have to be determined. The difference in the power losses in single and multiple actuator use is significantly different. This means the time other actuators would be used while hammering should be investigated. The versatility of the work done with a hydraulic hammer makes defining a work cycle difficult. Tasks include breaking hard boulders to demolition of concrete. The actual time hitting the target can also vary. In some situations, the hammering time can be only a few seconds and a large amount of time is consumed in maneuvering the targets to be hit. Some situations might need long continuous times of hammering with feeding force applied by the cylinders simultaneously.

In Chapter 6, four concepts for hammering with electric excavators were evaluated. With respect to the energy efficiency, the electrohydraulic power source, linear motor, and pneumatic-electromechanical hammer concepts show improvement to the conventional hammer system. The efficiencies are shown in Table 7 The electromechanical concept shows similar energy efficiency as in the conventional hammer due to the poor efficiency of the clutch. The electrohydraulic power source has an advantage in technical maturity. Utilizing the existing hammer with a more efficient hydraulic system gives a simple solution for improvement in efficiency. The limiting factor is still in the conversion of energy from electrical to hydraulic. The system would require a more efficient hydraulic hammer to reach higher levels of efficiency. Use of a hydraulic hammer with adjustable blow energy would improve the system. With the controllability of the power source and the hammer, the efficiency of the hydraulic system could be maximized.

Table 7. Efficiencies of the four concepts and the conventional hammer system

Concept	Total efficiency
Conventional hammer	36 %
Electrohydraulically powered hammer	51 %
Linear machine hammer	68 %
Pneumatic-electromechanical hammer	75 %
Electromechanical hammer	41 %

The other concepts may lack in technical maturity but the potential for a more efficient hammer is higher with them. The shortest energy flow of the linear machine gives it great potential for low energy consumption. Transforming the electrical energy into the kinetic energy of the piston minimizes the chance for losses in the system. The linear machine can also reach high levels of controllability compared to the other concepts. Fully controlling the blow energy and frequency is a highly desired feature. The uncertainty in the linear machine structure is a limiting factor. The ability for the linear motor to produce high enough forces and be able to withstand the high stress caused by hammering work needs to be proven. The pneumatic-electromechanical hammer does not have the controllability of the linear machine but the technology behind it is more mature. With the pneumatic-electromechanical hammer, the ability exists to scale the striking mechanism in the handheld machines to a size used in excavators. It might not be a reasonable concept for the whole range of hammers, but the features may satisfy the requirement of small range hammers. The electromechanical concept has the potential for high efficiency, but the striking mechanism is severely immature. The transmission of power to the piston is the most challenging part. The level of controllability affects the complexity of the electromechanical system.

Efficiencies of the different components in the concepts are estimates made from similar solutions in different applications. The efficiency in the implementation of the technology in hammering can be difficult and depends on different design factors. The control is also a crucial factor. In the clutch mechanism, the efficiency could be raised with precise control and measurement of the piston.

As seen in Chapter 6, the concepts can bring multiple different features in addition to the energy efficiency. While it is important to analyze the possibilities a new technology can bring to a device, the needs and requirements for the features must be considered. The features required and desired by the user may differ drastically from the features a machine can be engineered to perform. The variety of work performed with hammers is large and the use varies for different size ranges. A user who operates a small hammer with a micro excavator from time to time might desire different features than a mining contractor with multiple shifts of hammer-only work per day. For example, the controllability of the hammer might not be a priority for the first user, but the contractor might place it high in the priorities. In addition, almost without exception, more features in the hammer lead to higher cost. Currently, the hammer industry exclusively includes hydraulic hammers which use similar working principles across the whole range of hammers. The addition of electric hammers might separate the weight classes based on typical use into different working principles. For example, small range hammers might include the pneumatic-electromechanical principles while larger machines could consist of linear machine technology. The different concepts also bring different freedoms in design features compared to a conventional hammer. For example the striking piston size and shape can be modified in different ways.

7 CONCLUSION

This thesis began with a literature review on hydraulic excavators. The state-of-the-art LS system is inefficient and causes high losses in multiple actuator situations. The electrification of excavators is getting more popular for reduction of emissions. The most common solution for electrifying an excavator is replacing the diesel engine with an electric motor and a battery. The hydraulic system is still a valve-controlled system. The limited energy storage calls for improvement in the energy consumption of the hydraulic system and actuators. The hydraulic hammer was introduced in Chapter 3 to explain the application, operating principle and demands of the attachment. For the electrified hammer concepts, the possible technology was reviewed in Chapter 4.

The literature review gave background to measure the power losses in the excavator while using a hydraulic hammer. The loss in the hydraulic system was measured in multiple situations. A 25 % loss in power was measured when the hydraulic hammer was the only actuator used. In a situation where a cylinder was used simultaneously with the hammer, a power loss of 49 % was calculated. The results showed that a power loss due to throttling was significant when using only the actuator but can rise even more depending on the duration of multiple actuator use. The measurements showed that the power losses in hammering are similar to what they are in conventional excavator work.

Four concepts with different operating principles were designed to gain higher energy efficiency while hammering. The concepts were also reviewed qualitatively for an overall impression of the concept. All four concepts showed improvement in efficiency compared to the conventional system. The electrohydraulic power source gave a 15 percentage point increase in energy efficiency with mature technology. The electric powered hammer concepts have high potential for significant efficiency improvements, but they lack in technical maturity. The linear machine has very high controllability and 32 percentage point increase in efficiency. Meeting the force and speed requirements of hammering is still under research. The pneumatic-electromechanical hammer offers a 39 percentage point increase in efficiency and a fairly mature hammering mechanism. The scalability of the concept limits it to the smaller range. The pneumatic link still requires research in higher loads. The compression ratio of the pneumatic link affects the efficiency. The electromechanical solution requires more research. The high frequency clutch mechanism is immature but, with correct timing, the losses could be minimized and the efficiency could be improved.

The measurements could be improved by measuring the pump efficiency and the power of the cylinders. However, to evaluate the total efficiency, a work cycle would have to be determined. Hammering work in different applications could be measured and work cycles could be determined based on the measurements. The effect of the hammering could be compared to traditional excavator use. With the concepts giving more features like controllability, the most effective way to break material with a hammer should be investigated. Research on the losses in the pneumatic link should also be researched, and the kinematics of the striking piston and piston should be understood. The use of an electrically controlled hammer with an electrohydraulic power source to improve the efficiency even more could be researched. The control of the power source and the hammer could present opportunities.

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