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ELECTRIFICATION OF EXCAVATOR

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Abstract: *When using work machines in enclosed sites a significant cost is additional ventilation. The need of additional ventilation can be partly or completely excluded by using electric driven work machines.*

For this study a JCB Micro excavator was chosen as a building platform. The 14 kW diesel powered engine with its required equipment was replaced with a 10 kW electrical motor. Four lithium titanate batteries, with a total voltage level of 96 V and a capacity of 60 Ah, powers the electric motor. The overall success of the project was evaluated with measurements, which compares the same excavator with the two power sources.

With electric drive while maintaining the same performance, the operating time was substantially reduced compared to diesel powered drive.

Key words: excavator, electrification, electric motor, electric drive

1. INTRODUCTION

When using excavators indoors there are a few things to consider. Firstly, the space of an enclosed location is limited. Usually this means smaller sized machines. Secondly, when working in enclosed spaces ventilation is usually at best weak. Additional ventilation has to be built for the exhaust gas outlet. This means that work site manager has to make plans and build the additional ventilation, which makes the use of an excavator indoors considerably more expensive than outdoors. The need of additional ventilation could in some cases be avoided if the work machines were powered with non-combustible engines.

This study aims to convert a working JCB Micro excavator to an excavator that runs entirely on electrical power. Even then the excavator has to be able to do the same tasks as prior to its conversion. This is evaluated by doing same set of measurements before and after the conversion to define the performance difference. Besides performance the operational time in both excavators are compared.

The conversion process is done with a low budget, so the outcome of the conversion is to be considered as an inexpensive prototype. The main objective is to get the excavator in working condition so that the measurements can be performed. Aspects like weatherproofing according to industry specifications are considered as additional features.

One fully electrical hydraulic mini excavator has been introduced in 2011. The manufacturer claimed this excavator was on par with their, at the time, current mini excavator in terms of performance and that its lithium-ion batteries could power the excavator for up to six hours of uninterrupted service. However, so far the excavator has not been made commercially available. [1]

Many excavator manufacturers are providing partially electric driven excavators named hybrid excavators. In these excavators the rotation of the cabin is generally powered with an electric motor. This system often utilizes regenerative breaking to slow down the rotation. An electric motor can also be integrated into the diesel motor output to provide additional power when the diesel motor needs to rapidly accelerate. These electric motors can be powered with super capacitors. When aforementioned systems are utilized the overall fuel efficiency is improved by about 20% compared to a conventional excavator. [2]

Recent studies in excavators have mainly concentrated on improving the overall fuel efficiency of hybrid excavators with different methods, such as improved control strategy and energy recovery. [2][3][4]

This article begins with the methods of this study. In methods the conversion process and the comparing measurements are elaborated. The conversion process consists of the disassembly, part selection and manufacturing, and assembly. After this the results of the project are shown. This means showing the outcome of the conversion process and the measurements. Finally, there is the conclusion, which in turn also includes the discussion of the results.

2. METHODS

2.1 JCB Micro

The converted JCB Micro excavator is powered by a diesel engine producing 14 kW at 2200 rpms. The excavator weighs 1.1 tons and has a fuel tank of 14 liters. The excavator is however not in original condition, as it has been modified for prior projects. The excavator has been fitted with electrically controlled proportional valves and a control unit. There will be no additional modifications in the hydraulics in this conversion process. Thus, the electrical motor will operate at same range of speed than the diesel engine but the difference in torque will affect the hydraulic pressure.

2.2 Fuel consumption measuring installment

To be able to measure the diesel consumption of the excavator for the measurements a fuel measuring installment was built. The setup can be seen mounted to the excavator in Figure 1.

On the right side of Figure 1 is the lower half of the measuring tube, which shows the volume of fuel. As the refueling has been done prior to a measurement, the volume in the tube is read from the scale. After the measurement the reading is taken again. The fuel consumption can then be evaluated from the difference.

Under the measuring tube is the fuel output and return. The output line leads to the input of the fuel rail of the diesel engine. As the flow rate of the fuel in the fuel rail is constant there needs to be a return for the leftover fuel, which in this case is lead to the return of the measuring tube.

Because of the small volume of fuel that fits in the measuring glass, there are four control valves which are used to switch the fuel source between the fuel tank and

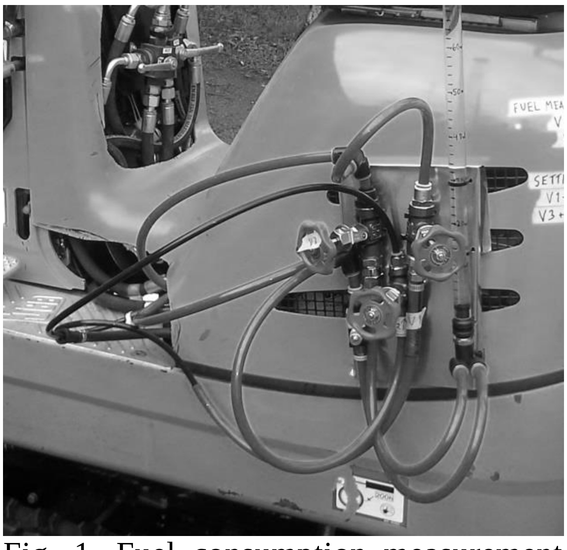

Fig. 1. Fuel consumption measurement installment.

fuel consumption measurement installment.

2.3 Measurements

To determine the outcome of the conversion a set of measurements for initial state were done. One of the main focuses when planning the measurements was to make them simple to perform. The individual measurements would thus have a smaller deviation, which in turn would make the comparison more valid. Because none of the researchers had experience in operating excavators, doing measurements involving fine series of movements would be very difficult to repeat accurately.
The test procedure consisted of a total of seven different measurements. The measurements were:

1. Driving forwards 50 meters.
2. Turning the cabin around 5 times.
3. Fully swinging the arm up and down 5 times.
4. Fully turning the boom left, right and left 3 times.
5. Offloading a sand pile.
6. Idling with full throttle.
7. Idling with no throttle.

All measurements were performed on level ground paved with asphalt, except for measurement #5, which was performed on even soil.
The different measurements were repeated 3 times, except for measurement #5 which was repeated twice, and measurements #6 and #7 were done once.
Main quantities in these measurements were time and fuel consumption. The fuel consumption measuring installment is described in chapter 2.2. The energy consumption for the electric driven excavator was read from the control unit, which has been described later in this chapter. For accurate fuel consumption the temperature of the diesel in the measuring device was measured before and after each measurement. Other parameters documented were weight of the driver, the ambient temperature, the engine temperature, and the hydraulic oil temperature.

2.4 Conversion process

All operations in JCB Micro are achieved with pressurized hydraulic fluid. These operations include turning the cabin, swinging the boom, arm and bucket, lifting and lowering the plow, running the continuous tracks, and using the extendable undercarriage.
The pressurization of the hydraulic fluid is achieved by running a hydraulic pump. The powering of the hydraulic pump is done with the combustion engine. The hydraulic pump and the combustion engine are connected using a transmission and a coupling. This is shown in Figure 2.
In this study these components, except for the hydraulic pump, were replaced with an electric drive.
Liquid cooled Golden Motor HPM-10KW was chosen for the electric motor [5]. As a brushless DC motor it is capable of producing maximum power of 10 kW at 96 V and has operational speed range of 2000-6000 rpm. With optimal driving conditions the motor can achieve 92% efficiency.

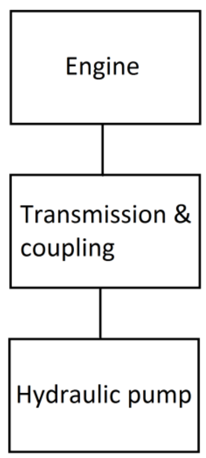

Fig. 2. Mechanical power chain of an excavator.

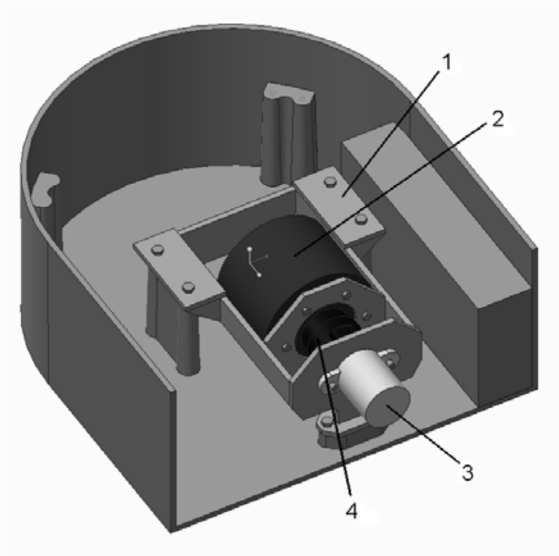

Fig. 3. Sheet metal structure (1) for the electric motor (2) and the hydraulic pump (3). Torsionally flexible coupling is also represented (4).

The coupling of the electric motor and the hydraulic pump was done using KTR ROTEX 42 GG torsionally flexible coupling [6].

The power source for the motor consists of four Altairnano lithium-titanate battery modules, each operating at 24 V and with a 60 Ah nominal capacity [7]. These batteries will be combined in series to produce the necessary 96 V to power the electric motor.

For operating the electric motor a ready-made control unit was used. The unit houses a Sevcon Gen4 controller, which was configured to work with the particular electric motor. All wiring from the electric motor and the batteries are connected to this unit. The unit also contains the on/off switch of the electric motor and an emergency stop button. The control unit is configured and values are read from the CAN-bus.

The energy consumption for the electric driven excavator was logged from an Altairnano controller, which was attached between the batteries and the control unit.

Speed regulation of the electric motor is achieved with a potentiometer, which is wired to the control unit. Besides the speed regulation there is a switch for putting the electric motor in drive mode.

For the electric motor and the hydraulic pump a welded sheet metal structure was built (Figure 3).

Additionally the mounting for the batteries and the control unit were built using store bought materials. Because the electric driven excavator is a prototype and consideration of keeping the two back mountings of the combustion engine (seen in Figure 3) intact the battery could not been placed inside the excavator and therefore had to be placed behind the driver. Because of the size of the prebuilt control unit, it had to be located outside the excavator above the batteries.

3. RESULTS

The excavators before and after the conversion were able to do comparable load intensive tasks (measurements #1-4, section 2.3) in approximately the same amount of time, which indicates that the excavators are capable of doing the same tasks. This statement is confirmed by that the electric driven excavator was able to perform in the same way as the combustion driven excavator when offloading a sand pile.

Table 1 and 2 shows the average energy consumption for each measurement,

Measure-ment #	Average fuel consumption [l/h]	Average energy consumption [kWh]
1	1.35	14.02
2	1.27	13.16
3	1.46	15.09
4	1.93	20.03
5	1.56	16.15
6	1.12	11.64
7	0.51	5.32

Table 1. Average fuel consumption for the measurements.

Measurement #	Average energy consumption [kWh]
1	2.96
2	2.55
3	3.76
4	5.59
5	3.10
6	1.35
7	0.46

Table 2. Average energy consumption for the electric driven excavator.

which are respectively for the combustion driven and electric driven excavator. Number of the measurement corresponds to the numbered list in chapter 2.3. Table 1 shows besides the calculated energy consumption the fuel consumption.

When comparing the tables there’s a big difference in the average energy consumptions between the excavators. When doing load intensive tasks the energy consumption of the electric driven excavator is approximately 20% of the energy consumption for the combustion driven excavator. The power consumption is lowered to approximately 10% when the task doesn’t demand much power, which is the case with the idling measurements (measurement #6 and #7).

By knowing the energy consumption, maximal energy storage and overall energy to work conversion efficiency of the excavator the operational time can be calculated. When calculating the operational time for the diesel driven excavator based on the measurement results, which is offloading of a sand pile (measurement #5), the operational time is approximately eight hours. The same calculation for the electric driven excavator gives approximately two hours operating time.

4. CONCLUSION

In this study the conversion process of a JCB Micro excavator from a diesel driven state to an electric driven state was presented. The conversion process mainly focuses around finding suitable electric motor, batteries and transmission. Also the mounting of these parts takes its time to plan and to build and especially the parameterization of the electric motor proved to be time consuming. Besides getting the electric driven excavator to function there was measurements made to compare the two excavators with different power sources.

The performance difference of the different excavators proved to be minimal. However, the operational time of the converted excavator is clearly reduced; despite of using four high-grade lithium-titanate batteries and having an advantage of the electric motor’s much higher efficiency. This means the operational time is about two hours (when using the full capacity of the batteries) depending on the power usage. With the fuel combustion engine and the 14 liter tank the operation time was calculated to be around eight hours.

The comparable short operational time for the electric driven excavator could be improved by providing the excavator with a smarter power controlling system, for example an automatic shutdown of the excavator when not operated. Also, by finely tuning the electric motor and using this motor at the optimal speed by implementing an appropriate gear ratio the overall efficiency could be increased.

The study shows that electric powered excavators can potentially be used in some cases where a fuel driven excavator is more expensive to use. The limiting factor of electric powered excavator is mainly the low capacity of the batteries and the long charging times of the batteries compared with the conveniences when using fuel driven excavators. Also the purchasing price of an electric driven excavator would be higher because of the expensive batteries.

5. REFERENCES

1. Takeuchi Manufacturing [US], Ltd. News Announcement: Takeuchi Introduces World’s First Fully Electric Hydraulic Excavator [WWW] http://www.takeuchi-us.com/www/blog/viewpost/43 (8.3.2014)

2. Hakgu, K., Jaewoong, C., Kyongsu, Y. Development of supervisory control strategy for optimized fuel consumption of the compound hybrid excavator. *Journal of Automotive Engineering*, 2012, **226**, 1652-1666.

3. Wang, T., Qingfeng, W., Tianliang, L. Improvement of Boom Control Performance for Hybrid Hydraulic Excavator with Potential Energy Recovery. *Automation in Construction*, 2012, **30**, 161-169.

4. Tianliang, L., Qingfeng, W., Baozan H., Wen G. Research on the Energy Regeneration Systems for Hybrid Hydraulic Excavators. *Automation in Construction*, 2010, **19**, 1016-1026.

5. Golden Motor [WWW] http://goldenmotor.com/ (2.3.2014)

6. KTR. ROTEX [WWW] http://www.ktr.com/root/img/pool/pdf/produktkataloge/en/en_gesamt/001_rotex_en.pdf (2.3.2014)

7. Altairnano. 24 V 60 Ah Battery Module [WWW] http://www.altairnano.com/wp-content/uploads/2011/10/60Ah-DataSheet.pdf (2.3.2014)

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