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Direct driven hydraulic drive for new powertrain topologies for non-road mobile machinery

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ABSTRACT

Tightening of emission rules and a desire to improve energy efficiency pushes even further the need for hybridization of non-road mobile machinery (NRMM). Consequently, this paper illustrates potential of the application of directly driven hydraulic drive (DDH) for NRMM from an energy efficiency point of view. The control of the DDH system was implemented directly with a servomotor driving a pump without conventional hydraulic control valves. Angular speed of the servomotor, in-coming oil flow from the pump, and out-going flow to the hydraulic motor determined the velocity of the double-acting cylinder piston. An earlier study by the authors presented that the hydro-mechanical losses were dominant in the original DDH setup. Resulting theoretical investigation indicated that the best scenario efficiency for DDH was estimated to be 76.7%. Therefore, this paper provides a detailed analysis based on Sankey diagrams of various powertrain topologies with DDH. This study of powertrains illustrated that DDH has the highest impact with 174% efficiency improvement with an electric NRMM powered by batteries instead of a conventional topology.

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1. Introduction

Energy efficiency is becoming crucial in all fields of engineering as a result of tightening of emission rules [1]. At present, valve-controlled hydraulic systems with throttled pressure, losses and lower efficiency are applied commonly in Non-road mobile machinery (NRMM). Currently, industry is investigating for compact, efficient and powerful solutions for control and powertrain applications in NRMM. Similar demands are recognized in industrial hydraulics where a flexible layout of production, lower energy demand, and avoidance of additional heat and noise. New technological solutions are needed to further reduce fuel consumption and improve energy efficiency to fit new governmental requirements. Hybrid technology has been identified to be one of the key solutions to achieve these targets. There are already some examples of NRMMs in the market that provide hybrid solutions [2,3]. In these, the hybridization targets mainly in improving performance and fuel economy. In [4], a 20-ton parallel hybrid excavator by Komatsu with supercapacitor achieved up to 41% energy savings. A Hitachi serial hybrid loader with a battery as energy storage achieved energy savings of 25–30% depending on the cycle [5]. Typically, the diesel engine is running hydraulic pumps and the mechanical powertrain. In these, the diesel can be supported by electric motor/generator located after the diesel engine. In [6] the challenges faced by researchers and NRMM manufacturers were underlined, such as energy storage, control of generation energy and cost in general. These provide new dimensions into the control of generation and distribution of electric energy. On the other hand, the development of an electric and plug-in powertrain proposal for NRMM is facing identical problems in the automotive sector related to battery technology and its charging issues. In electric vehicles – especially passenger cars but also busses – there is now urgent need to define charging systems and develop needed infrastructure. Recent research concentrates on charging of electric vehicles [7–9], as this is essential in order to ensure wider acceptance by customers and facilitate more electric vehicles on roads. This need is underlined also by politics in EU.

Before these solutions enter wider markets, it can be hypothesized there will be a need to have even more sophisticated means to utilize electric energy for creating hydraulic pressure on board and only when it is required. Currently, a trend for a decentral-
ized power network opens up new approaches for hydraulic- and hybrid circuits for NRMM [10–12]. As a result, electro-hydraulic systems with motor- or pump-controlled systems are observed on the market and research areas [13–18]. These electro-hydraulic systems are attracting an attention of industry due to advantages of their size-to-power ratios and the ability to produce large force and torque only on demand. These technologies provide opportunities, compared with traditional systems, a compact structure and high efficiency with a speed regulation loop without conventional valves [19,20]. All these features can be beneficial in creating new powertrain topologies in NRMM.

Consequently, the development of electro-hydraulic compact systems motivates current research activities, however no efficiency analysis was found concerning their application in the NRMM systems. Therefore, the effect of a direct driven hydraulic setup (DDH) on the efficiency of a variety of powertrain topologies
is investigated in this paper. This study is realised by either calculating, or measuring the efficiencies of various used components and calculating their common effect on the topologies.

This paper structure as follows. In Section 2 scheme and the principles of the DDH system are described in detail with a theoretical system component evaluation and validation of efficiencies by measurements. Topologies of NRMM's powertrains and their component efficiencies are introduced in a system study in Section 3. Sankey diagrams are utilized in Section 3 to analyze efficiency of the conventional and alternative powertrain topologies. Section 4 and 5 contains discussion and concluding remarks.

2. Test setup description: detail introduction of direct driven hydraulics

Simplified schematics of DDH test setup are demonstrated in Fig. 1a. The setup uses a speed-controlled electric servomotor drive with dual rotating hydraulic pump/motors to directly control the position of the double-acting cylinder via a T-gear. First hydraulic pump/motor P1 creates a flow depending on the rotating speed of the servo motor and, simultaneously with the same speed, the second pump/motor P2 pumps oil out from the cylinder. A LabVIEW program for the electric drive controls both the electrical and hydraulic sides of the system.

The power source of the frequency converter in the current setup is an electric network, and an embedded brake resistor acts as the 'energy storage'. For the measurements of the system, a frequency converter software was utilised to record the rotating speed and estimated torque of the PMSM with help of an incremental encoder as the motor rotor position feedback. A power analyser Hioki 3390 with a sampling time of 50 μs was utilised for measuring the voltages, currents and active powers. Gems 3100R0400s pressure transducers [21], installed at the pump's inlet and outlet, was used to measure system pressures. The actual velocity and position of the cylinder's piston rod (C-10-60/30 × 400 manufactured by MIRO) were measured with a wire-actuated encoder SIKO SGI (IV58M-0039) [22]. Utilised components were chosen for the test setup, as they were readily available or fast to purchase at the time of construction. The components do not have any specific properties for this kind of application. Figs. 1b and c illustrate photographs of the test setup.

The following Section 2.1 introduces an evaluation of the DDH components in detail and illustrates the efficiency of the test system based on background research and theoretical information provided by component manufacturers with the best scenario approach in mind. A theoretical evaluation verified by measurements is presented in Section 2.2.

2.1. System component evaluation

The prime mover of the DDH system is an electric machine controlled by a frequency converter. The servomotor in the DDH setup is a 3 kW PMSM (Unimotor 115U2C) by Emerson Control Techniques [23]. In general, permanent magnet synchronous servomotor is characterized by its high efficiency and high overload capability. Estimation for the total efficiency of the servomotor was

![Efficiency chart of different hydraulic pump types](image-url)
made based on the motor parameters and vector equivalent circuits for a PMSM illustrated in Fig. 2. For detail explanation see Ref. [24].

Fig. 3 illustrates the efficiency chart for the servomotor made based on the estimation. The efficiency contours are closed and have large areas with efficiencies above 90%. Moreover, the efficiency islands are typically located in areas of nominal speed and rated power. In electric motor’s case it may also be similar situation to diesel engine that the motor–controller combination is not operating in its optimum area.

In the experimental study of the DDH, a 400 V servomotor with a frequency converter Unidrive SP1406 by Emerson Control Techniques [26] was utilised. The Unidrive provides speed, torque, and motion control for the servomotor with efficiency in the range of 97–98%.

Fig. 4, depending on the operating point of the hydraulic pump/motor unit on its performance curve, the relationship between flow and hydraulic losses varies significantly. The pump/motor internal leakage increases with the higher operating pressure and lower fluid viscosity. These variables are difficult to take into account in the calculation of unit efficiency as they vary with time and temperature. Therefore, in our test setup, the power

Next DDH setup components under investigation are the hydraulic ones. Main hydraulic component is the pump. In the content of this research, a hydraulic motor is utilised as a pump, therefore, it will be named pump/motor. In the experiments, two hydraulic motors of type XV–2 M by Vivoil [27] were utilised with a fixed displacement of 14.4 and 22.8 cm³/rev for P2 and P1 respectively. These hydraulic motors are also capable of working as a pumps. According to
losses in pump/motor are assumed to be 15% based on the best scenario approach.

A double-acting cylinder is utilised as the actuator in the DDH setup. Cylinder’s overall efficiency is dependent on the frictional losses associated with the piston and the rod moving during its stroke. Frictional losses depend on multiple characteristics such as pressure difference across the seal and its material, sliding velocity, temperature, time, wear, and direction of the movement. According to Ref. [29] total seal friction of a hydraulic cylinder varies between 2–5% of the total cylinder force, therefore, the cylinder efficiency was assumed to be 95% for the best scenario approach.

A mechanical T-gear is utilized as a coupling between the two pumps/motors and its efficiency varies between 98% and 99%. This value does not significantly affect the total efficiency of the DDH; therefore, this value is neglected from analysis. For this study, electric cable losses and hydraulic pipe losses were also considered neglectable and omitted.

Taking into account all the components’ best scenario efficiencies, the DDH setup overall efficiency can be estimated to be 76.7%. Fig. 5 illustrates the best scenario of the DDH considering the following efficiencies: pump/motor – 85%, electrical machine – 95% and double-acting cylinder – 95% (efficiency of the frequency converter is not included).

Following Section 2.2 introduces measurement results which are utilised for validation of efficiency values.

2.2. DDH efficiency measurements

This section presents analysis of the DDH based on measurements. In order to determine the behaviour of the DDH system, efficiency charts for the lifting and lowering operations of the hydraulic boom are created. Fig. 6 displays the measurement results for the total efficiency. The experimental setup was tested with a payload of 175 kg with a motor speed range from 300 to 500 rpm. In Fig. 6 positive motor speed corresponds to lifting, negative speeds correspond to lowering motions. The electro-hydraulic efficiency of lifting is defined as a ratio of the input energy from the motor to the potential energy of the load, and for lowering as a ratio of the recovered energy to the potential energy. The efficiency curves have been calculated from the measured data by using equations explained in detail in [19]. As illustrated in Fig. 6, the total lifting efficiency varies with motor speed from 50 to 20%. During lowering, total efficiency is in the range of 8–32% depending on the motor speed and payload.

Fig. 7 illustrates the measured Sankey diagram of the DDH with motor speed 300 rpm and payload of 175 kg (efficiency of the frequency converter is not included).

Comparison Figs. 7 and 5 illustrates a significant underestimation of hydro-mechanic losses and the same time potential of improvement of DDH by better sizing and selection of components. This potential is especially highlighted in application of DDH for hybrid transmissions. Therefore, following Section 3 will apply DDH to known powertrain topologies as a system study.

3. Powertrain study

Section 3.1 begins by presenting the single components of powertrain topologies which were not mentioned earlier (in Section 2.1). Each component is analysed from efficiency point of view similar as in Section 2.1. Efficiencies for the following system studies are summarised in the end of the section. Section 3.2 introduces the alternative powertrain’s topologies and their efficiency analysis by means of Sankey diagrams.

3.1. Powertrain components

Most of the operations functions in NRMM are powered by hydraulics. Usually, in conventional machines the powering of the hydraulic pump is achieved directly with a combustion engine. The hydraulic pump and the combustion engine are connected using a transmission and a coupling as illustrated in Fig. 8.

Depending on the working cycle and dimensioning of the system, the engine may be most of its operation time very far away from its optimum efficiency. Fig. 9 illustrates example of a diesel combustion engine efficiency map. According to Ref. [20], diesel
combustion engine operating efficiency depending on the working cycle is normally about 20%, and that is only half of the maximum efficiency 40% in optimum operating region. Due to this fact, the total efficiency of any powertrain based on an engine is automatically low.

A conventional proportional control valve is the main control unit for on-board hydraulics, which ensures correct direction of the oil flow in the system. It was demonstrated in Ref. [30] that efficiency of a hydraulic boom is only 60% due to the characteristics of conventional valves, which have high flow resistance and internal leakage. In this study, valve losses follow the best-case scenario and are assumed to be 20%.

So far, a conventional powertrain was introduced and its disadvantages. To meet CO₂ requirements, hybrid and electric solutions for powertrains are created. Alternative sources of energy for realisation of new topologies for non-road mobile machinery are also required. In this research, battery is chosen as a source of energy. Fig. 10 illustrates an example of lithium–titanate battery's Coulombic efficiency. Highest efficiency region is located in low current and high state of charge regions. According to Ref. [31], efficiency of 95% covers working region of NRMM and this value will be utilized for the analysis.

In following Section 3.2 are the component efficiency data from the current section and Section 2.1. These were utilized to calculate the overall efficiencies for the conventional and alternative NRMM topologies.

![Fig. 9. Example of the diesel combustion engine efficiency map.](image)

![Fig. 10. Calculated efficiency chart of a lithium–titanate battery [31].](image)

3.2. Powertrain topologies' efficiency analysis

This section introduces the efficiency analysis of conventional and alternative powertrains by means of Sankey diagrams. Table 1 contains summary of the utilized theoretical efficiencies for the Sankey diagrams. Table 1 is the prime source of data to define best scenario operation conditions for NRMM.

Figs. 11–14 demonstrate theoretical efficiencies for the conventional and alternative NRMM powertrains in optimum operating region based on the above-mentioned data. The theoretical total efficiency of the NRMM system was calculated by multiplying the individual component’s efficiencies. Each subsection ends with a brief presentation of how the change of components effects the different powertrains.
Fig. 11 illustrates a conventional powertrain, where 100% is input energy from fuel.

According to Fig. 11, significant concentration of losses of the powertrain is located in diesel engine, where 60% is generally discarded as heat loss. Total system efficiency in conventional NRMM is 25.8% in optimal operational region.

In order to compare the disadvantages of the conventional NRMM system, the proposed hybrid and electric topologies are analysed in identical way.

Fig. 12a displays a hybrid topology for NRMM with DDH. Generator (G) collects energy generated by the engine; as a result the engine can be forced to constantly work in the high-efficiency zone. In this topology energy is transferred using direct current directly to DDH, where the actuator is driven directly by an electrical motor. Fig. 12b illustrates hybrid powertrain with measured DDH efficiency. In this topology, DDH losses are second biggest after the engine. Fig. 12c presents the theoretical efficiencies of the hybrid topology with the best case scenario of the DDH. The best case scenario total efficiency of the powertrain of this system is 27.5%, which is slightly higher compared to the conventional powertrain’s 25.8%.

Fig. 13a presents the electric version where the original engine and generator of the NRMM was replaced with a battery. A frequency converter is used to supply and control the electrical machine. Pump delivers the flow to all the actuators in the system thru conventional valves that control the actuator motions.

Fig. 13b illustrates the Sankey diagram for the electric NRMM topology with a conventional hydraulic line. Most significant losses are due to the valves in hydraulic section of the system. Despite this fact, overall efficiency is higher compared to conventional engine driven powertrain (Fig. 11a).

In Fig. 14a is illustrated the second electric approach where the engine is replaced with a battery, frequency converter is utilised to supply the ac network of the machine, control the charging of the batteries and maintain voltage levels in the system. Conventional hydraulics including the valves are replaced with the DDH per actuator.

Fig. 14b illustrates a Sankey diagram where the total efficiency of this powertrain topology is 46.1% which is significantly higher compared to the conventional system. By applying the best scenario of DDH in Fig. 14c, efficiency of the electric powertrain is increased from 46.1% to 70.7%.

Following section contains overall discussion about possible improvements in the powertrain, which can be achieved by changes in the utilized topology.

4. Discussion

The experimental investigation of the DDH demonstrated that achieved measured performance was up to 50%. However, the limi-
Fig. 12. (a) Schematics of hybrid powertrain with a DDH, (b) Sankey diagram of the series hybrid powertrain with measured DDH efficiency, (c) Sankey diagram of the hybrid powertrain with best case scenario DDH efficiency.

The dominating factor of the DDH is hydraulic losses. The best scenario values of 76.7% can be achieved with optimal selection of components for the DDH. Based on the Sankey diagrams, it can be seen that the optimisation of the DDH’s total efficiency is important. For example, with DDH optimized, the powertrain efficiency increased from 17.9 to 27.5% in hybrid (Figs. 12b and c) and in electric proposal from 46.1 to 70.7% (Figs. 14b and c).

Combustion engine is clearly the most non-efficient part in any powertrain and it was shown that optimizing of hydraulic components and locating them closer to the actuators (creating the best scenario DDH) gives an improvement of 7% (Figs. 11b and 12c) of overall efficiency of NRMM’s powertrain.

From electrification of a conventional NRMM with valve-controlled hydraulics it is possible to get a 118% improvement based on comparison of Figs. 11b and 14b. It is worth mentioning that electric proposal is limited mainly by battery capacity and techno-economical boundaries of today’s technical solutions.

The comparison of Figs. 11b and 14c indicated that, 174% increase in overall powertrain efficiency can be achieved by converting conventional NRMM to electric topology with the best
case scenario of efficiencies of a DDH. Improving efficiency would besides the energy savings, reduce the demand of cooling which is one of the system issues of today’s machines in terms of volume, costs, weight and maintenance.

Assumptions that efficiency of a combustion engine is constant, engine is working in its maximum efficiency and excluding working cycle is very optimistic and simplifies things significantly, which causes non-significant difference between the conventional and hybrid topology with regards to efficiency (Figs. 11b and 12c). Despite that, effect of the DDH is clearly visible in the electric powertrain proposals.

Therefore, the study indicates that DDH can increase the efficiency of NRMM. Its full potential can be only realized if NRMM is converted to be fully electric. It is important to also mention that current study analysed only linear movements of NRMM and without energy regenerative features of the DDH. For future development, these features should be taken into account.

5. Conclusion

Tighter emission and energy efficiency requirements demonstrates a need for hybridization of non-road mobile machinery (NRMM). This paper investigates a directly driven hydraulic drive’s (DDH) effect on the efficiency of various NRMM powertrain topologies and analyses them with help of Sankey diagrams. DDH’s measured energy efficiency varies up to 50% depending on the direction of the cylinder’s motion and the motor speed. The best scenario efficiency for the DDH was estimated to be 76.7%. According to the Sankey diagrams, the hydro-mechanical losses dominate in the DDH and should be improved. Despite this, the DDH powertrain without conventional control valves illustrated a 174% best scenario increase in overall powertrain efficiency that can be achieved by converting a conventional NRMM to electric topology. Therefore, further study on optimising the DDH hydro-mechanical components and investigation on the regenerative energy modes is vital in order to explore all benefits of proposed powertrains.

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Fig. 14. (a) Schematic of an electric powertrain with DDH hydraulics, (b) Sankey diagram of the electric powertrain with measured DDH efficiency during lifting, (c) Sankey diagram of the electric powertrain with best scenario DDH efficiency.

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