Trends and some recent developments in Mobile Hydraulics

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Abstract: Fluid power drives are especially competitive in applications where no electric power net is available. This is generally found in mobile hydraulics where hydraulic power generation is achieved via a combustion engine. The paper starts explaining those differences and the systematic of hydraulic power control. Major developments of drive trains are treated and for some examples its efficiencies are shown over the whole speed range. Ideas of the early eighties to regain brake energy become important again as fuel prices increase and the awareness of saving CO_2 greenhouse gases gains momentum. Therefore some modern concepts are discussed including improvements in savings and performance. The second part treats power distribution from a single hydraulic power source usually by a displacement controlled pump driven by the combustion engine to supply work hydraulics. Now developments in industry with regard to load-sensing and electro-hydraulic control are presented. The paper is an extend version of a presentation at the congress 'The Future of Power Transmission' in Italy in May '07 [10].

Keywords: Fluid power drives, mobile hydraulics, drive concepts, design,

1 Introduction

For the next decade we can assume that the combustion engine will play the mayor role as a primary power source in mobile applications. This will strengthen the role of fluid power. The reason can be taken from ***Figure 1***. In stationary applications the power source is usually the remotely located electricity generating power plant feeding the electrical power net.

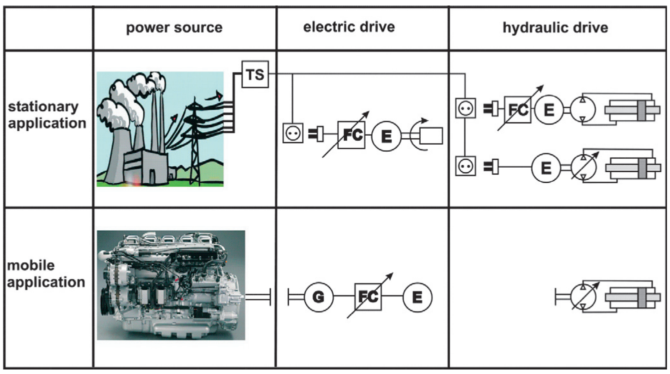

Figure 1. *Hydraulic power generation in comparison*

A conversion of electrical to mechanical power is mandatory and usually achieved by an electric motor with constant speed or with variable speed via a frequency converter. Thus the hydraulic drive solution has to compete with the electric drive solution needing one extra power conversion. Even with this uneven start conditions the hydraulic drive has advantages in case huge linear forces are required (presses, machine tools and injection molding machines) and where spacing and dynamic performance are essential [9].

However, for mobile applications we face even conditions from the beginning. The combustion engine powers a generator to feed a frequency converter or a variable pump to feed a cylinder or a motor. With this in mind ***Figure 2*** points out the major characteristics of hydraulic drives.

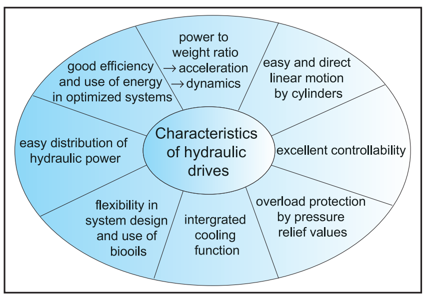

Figure 2. *Characteristics of hydraulic drives*

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Power to weight ratio is especially important in case of mobile equipment. It also features the advantage of excellent acceleration capabilities associated with high dynamics. Easy linear motion was already mentioned and excellent controllability is possible via modern pump and valve controls as we will see in later treated examples. Overload protection is provided by simple pressure relief valves and the heat is drained out of the hydraulic circuit via its fluid. Circuits are easy in design and flexibility and today's machines allow the use of biologically fast degradable synthetic esters as pressure media. Hydraulic power is easy to distribute to wheel drives and work hydraulic and the efficiency is superior to that of mechanic drives as we will see in the next chapter.

Before starting to design and lay out a hydraulic circuit one needs to focus on the systematics of hydraulic power control In ***Figure 3*** it is divided into mode of power control on the horizontal axis and into mode of hydraulic power supply on the vertical axis. Control is possible via resistance or displacement of hydraulic valves or displacement units. Concerning power supply we can distinguish between impressed flow and pressure. Quadrant I is generally used for automotive steering systems and quadrant II for standard servo hydraulic solutions where dynamics is more important than efficiency.

In mobile application we see the use of quadrant III and IV for drive solutions. Some examples are discussed in the next chapter. For work hydraulic the situation is somewhat more complicated as can be seen by the examples discussed in chapter 3.

2 Drive trains

In order to distribute combustion engine power to the wheels a transmission is required. Its task is to transform speed and torque to the requirements at the wheel.

Figure 4 displays the qualitative characteristic using a four speed manual transmission. The maximum power hyperbola is set by the engine capability. Depending on the gear choosen the hyperbola is only touched in a few areas. Thus making best use of the engine a lot of gears are required. Therefore the best fit can be achieved only with a continuously variable transmission (CVT).

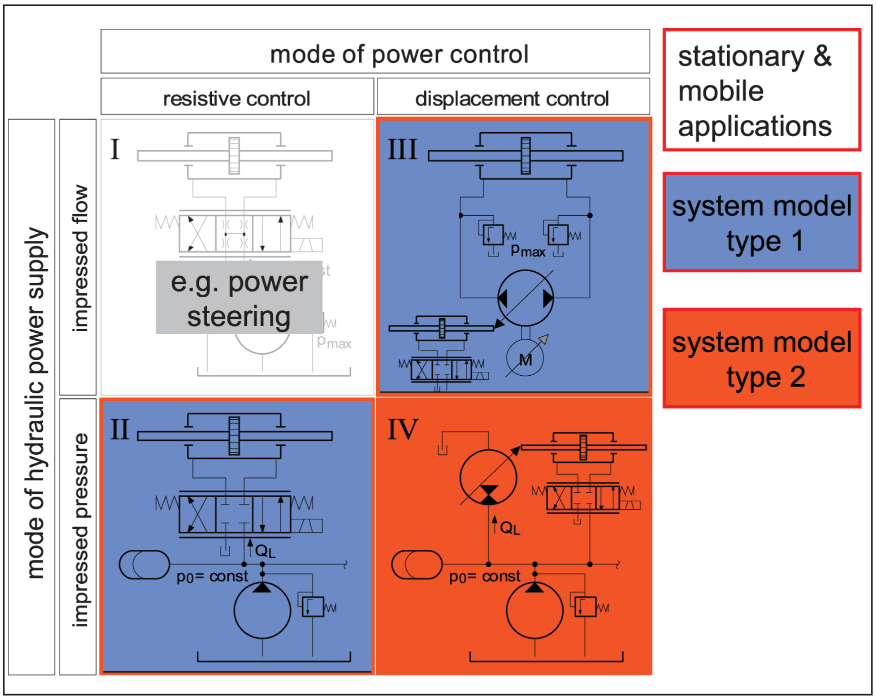

Figure 3. *Systematic of hydraulic power control*

The effect is shown in ***Figure 5*** using the motor characteristic of a typical diesel engine.

Comparing a CVT with a four speed manual transmission with torque converter leads to 12 % fuel servings being able to move along the power line at partial load.

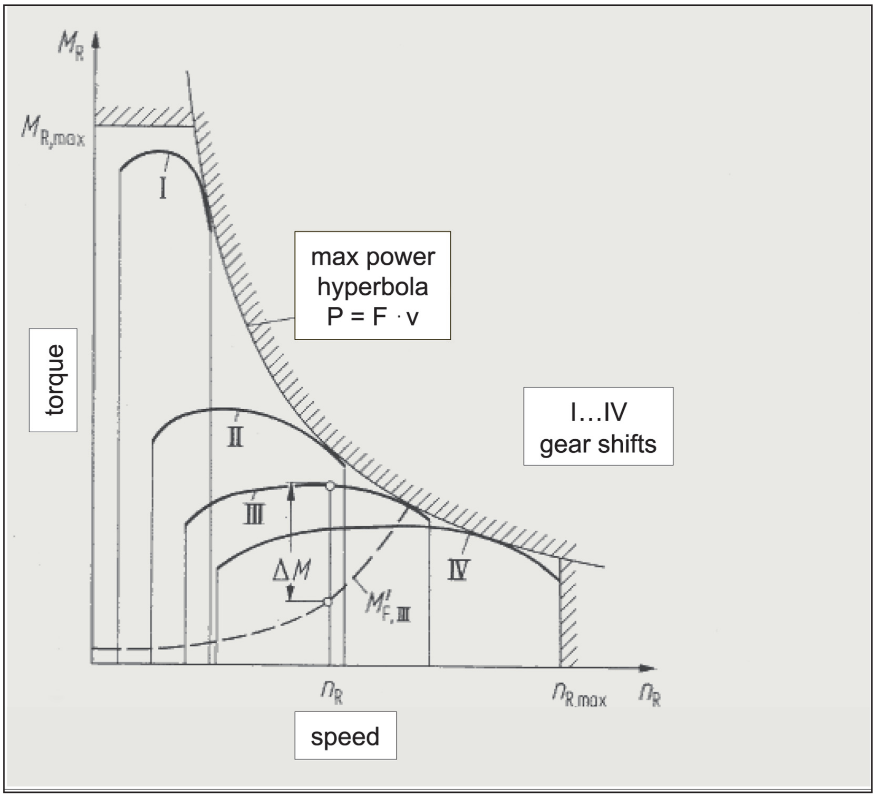

Figure 4. *Operation range for a 4 speed mechanical gear set*

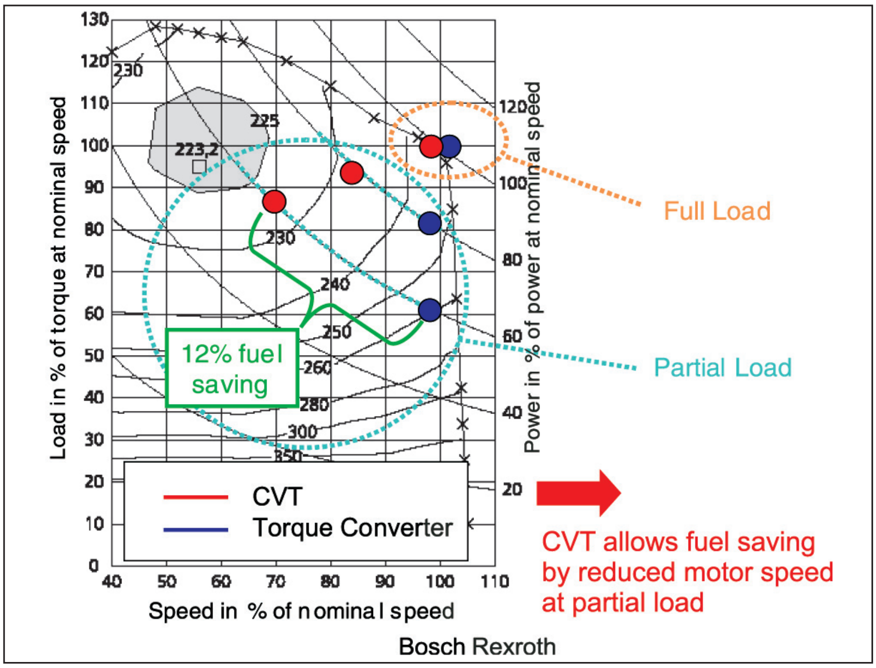

Figure 5. *Potential of fuel savings with CVT*

At IFAS of RWTH Aachen University together with the Universities of Braunschweig, Dresden and Karlsruhe a research project was started together with VDMA and a consortium of companies to simulate and investigate drive trains of mobile machines [5]. Goal is to build up simulation models for typical drive trains as can be seen in ***Figure 6***. These models include efficiencies of all gears, clutches and hydrostatic units from engine shaft to the wheel.

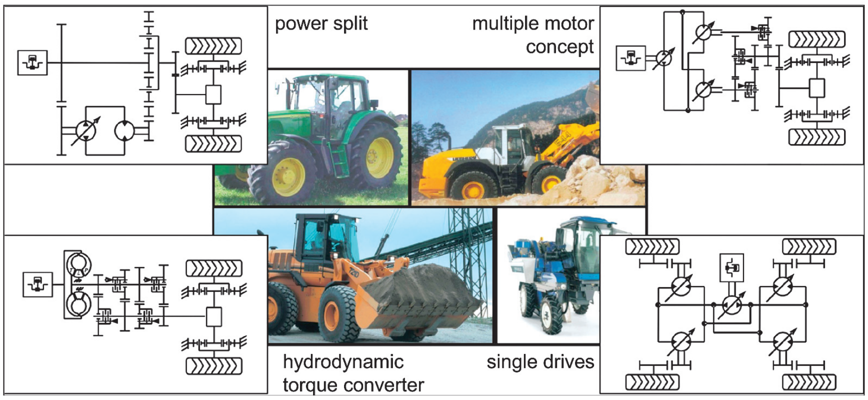

Figure 6. *Investigation of different drive trains*

An important part beneath simulation is to conduct real measurements of components and complete drive trains in order to prove the simulated data. Drive configurations investigated are:

- power split
- multiple motor concept
- hydrodynamic torque converter
- single drives

Obtaining comparable simulation data it was necessary to define and use a load cycle. Here the Y-cycle of a wheel loader was used to compare the different drive trains. Simulation results for the Y-cycle are given in ***Figure 7*** Different colours identify the efficiency with red standing for poor efficiency and green for a good one.

The dotted line represents the power hyperbola for 120 kW. In the upper left part results of the John Deere 6920 IVT power split drive is depicted. It limits pulling force for small speeds and features increasing efficiencies for rising loads and speeds. The multi motor concept simulates the Liebherr L 544 gear and exhibits good efficiencies over the whole speed range which decrease somewhat with higher loads. The torque converter drive train in the lower left is based on the O & K L 25 B and uses a four speed gear box. Islands of good efficiencies can be identified but at low speeds the efficiency decreases drastically. This is based on torque converter performance. The single drive simulation is not based on a realized drive concept. It was simulated for reasons of comparison with the other concepts. Without an additional gear box it only covers the area of small speeds with good efficiency except for very low speeds. Finally with ***Figure 8*** two concepts are compared directly. For this comparison actually used drive trains for wheel loaders are used. Those are the multi motor concept and the torque converter with gear box. Four working points are used as can be seen in the figure. Green bars represent the power output at the wheels. Blue colour stands for power losses in mechanical parts, red for those in the torque converter and orange for the hydrostatic units. While results in working points 2, 3 and 4 do not show significant differences we can see a clear advantage for the hydrostatic drive train solution in case of low speed and high pulling force.

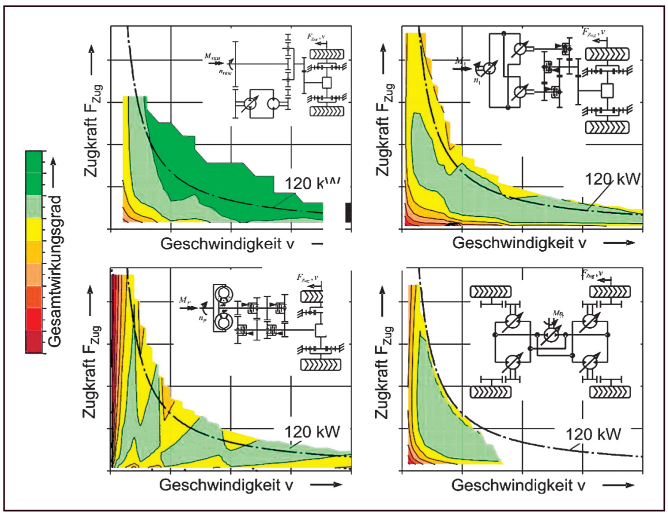

Figure 7. *Comparison of drive concepts*

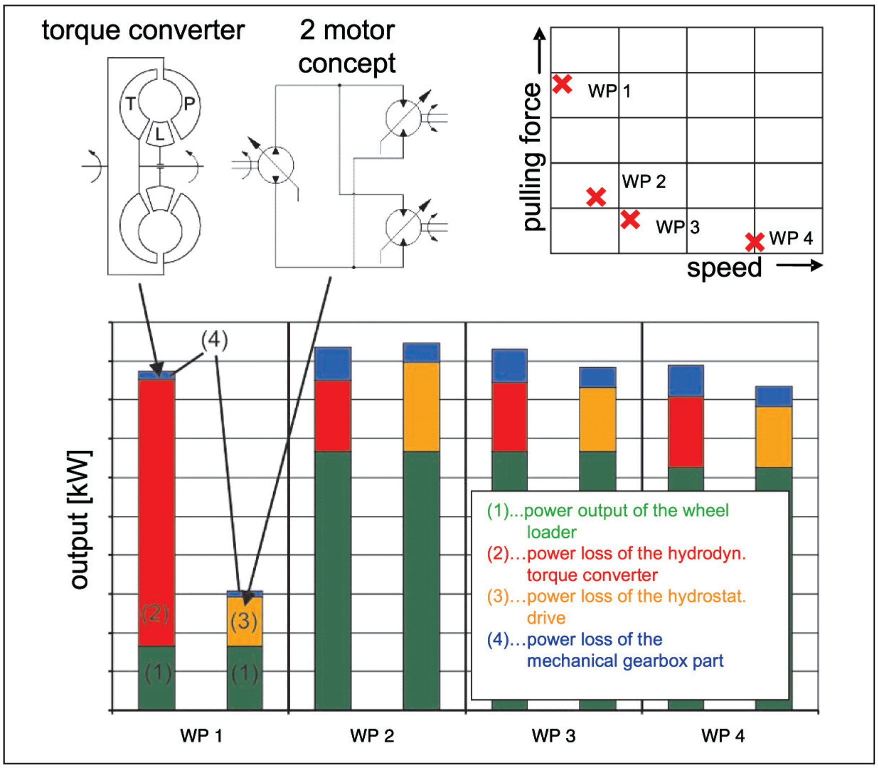

Figure 8. *Comparison of power losses*

An advantage of fluid power is the capability to regain brake energy. This is known for a long time [3] but only developments were pursued after energy crises in the early eighties and no concept really made it into large scale production. ***Figure 9*** is useful to describe the two principally possible solutions for energy storage and reuse. The closed circuit hydrostatic transmission feeds brake energy back to the pump running than as a motor.

In case of an asynchrounous electric motor the energy will be fed back into the electric net. Is a combustion engine used a flywheel is necessary to take up the energy in case it should not be converted to heat in the combustion engine.

This is different for the secondary controlled motor. Here a hydraulic accumulator can store and discharge energy. Pressure doesn't change its side as in the hydrostatic drive and in case of braking the unit goes overcenter running as a pump and feeds the accumulator.

It took almost a quarter century before the idea was used again for a development at Monash University together with Permo-Drive [13]. The schematic of operation is provided with ***Figure 10***. A variable hydrostatic unit capable of running as a motor or pump by going overcenter is placed into the drive shaft with the housing mounted to the chassis. The unit is called regenerative drive shaft (RDS). In case of static motion flow as well as displacement goes to zero. During braking the unit is displaced and pumps flow into the high pressure accumulator which is reused during acceleration to feed the unit than running as a motor.

The increase in acceleration performance is presented in ***Figure 11***. Desired speed of a 16 to military vehicle is obtained in about half of the time in case no RDS is installed.

Figure 12 displays a cross sectional view of the unit and provides an impression of the build in situation in the truck body.

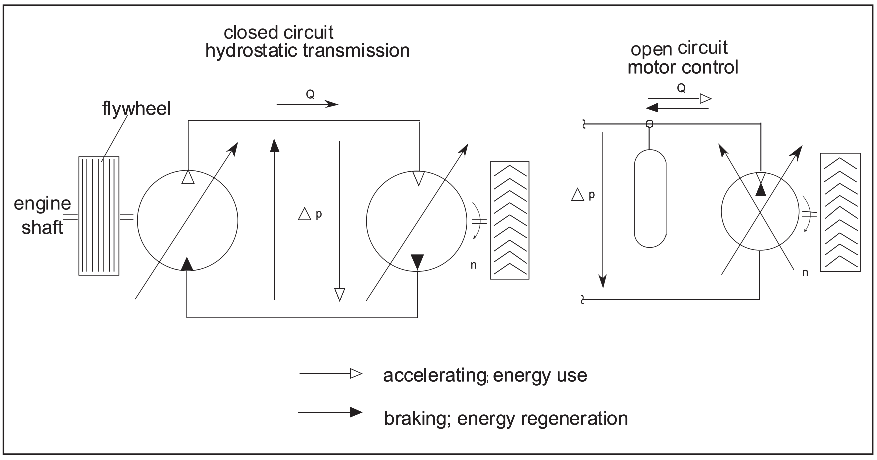

Figure 9. *Possibilities of regaining energy*

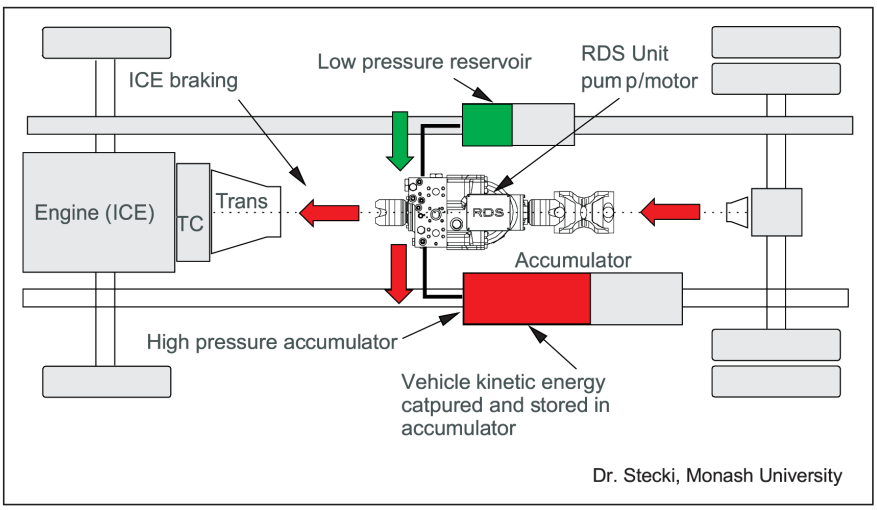

Figure 10. *Drive shaft integrated hydrostatic unit during braking*

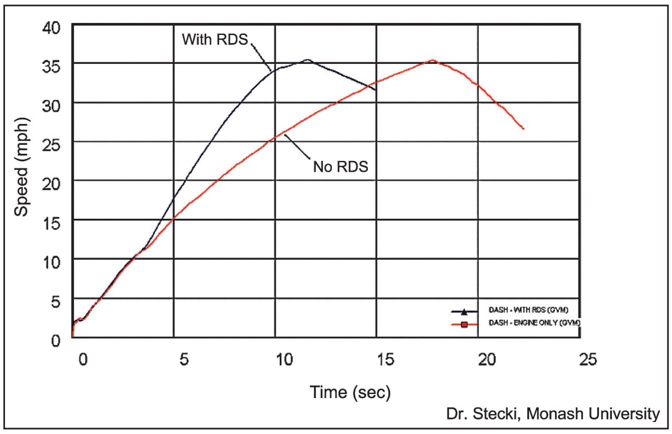

Figure 11. *Performance with drive shaft integrated hydraulic unit*

Another idea makes use of a displacement controlled unit that is added to existing drive shaft driven vehicles [11] as an add on. The unit is engaged and disengaged via a clutch and the high pressure accumulator is connected to the unit in case of charge or discharge, see ***Figure 13***. The coloured characteristic on the right hand side provides an idea of the accumulator size necessary for a certain vehicle mass at a speed from which it needs to brake and to which it has to accelerate after stopping.

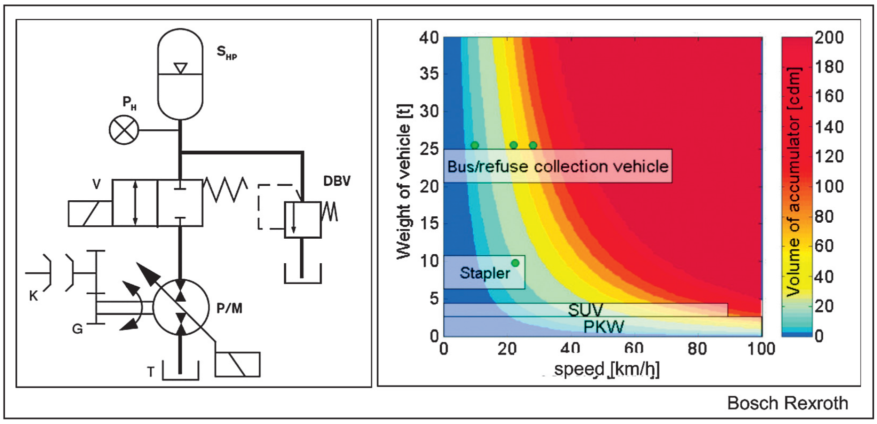

Figure 13. *Schematic of an add on unit and accumulator size*

For city buses and garbage trucks accumulator volume is calculated to about 30 to 60 l. In case a hydrostatic drive train is already in use the system needs to be converted from a closed to an open circuit as explained in the schematic in Figure 9. Finally ***Figure 14*** shows the potential of performance increase and the fuels savings of about 30 % that are gained.

The secondary controlled motor needs an adjustable displacement unit. In applications like cylinders this option is not given because cylinders with a continuously adjustable effective area are not known yet. This is the reason why load sensing is still in use in case one pump has to drive more consumers of hydraulic power.

Trends will be discussed in the next chapter. With a constant pressure supply a hydraulic transformer becomes necessary [12], [6]. It adjusts the hydraulic power at the cylinder to the required level by the control and feeds excessive power back to the hydraulic net. The principle is depicted on the right hand side of ***Figure 15*** while the left side shows a cross sectional view of a production unit [6].

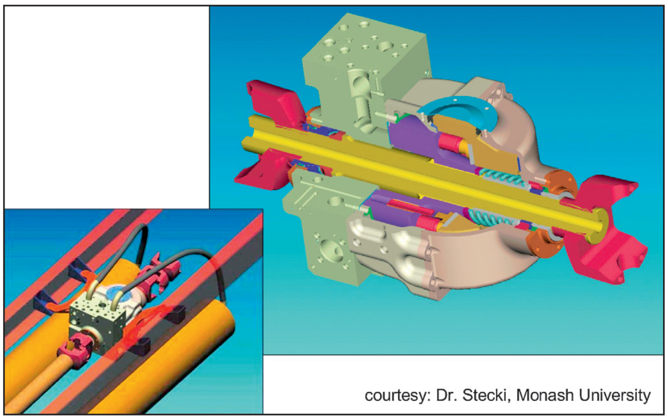

Figure 12. *Build in situation and cross sectional view of RDS*

A much simpler design was invented by the company INNAS, NL [1]. Here the control is realized by adding an extra port to the control plate and rotate it around its own axis as displayed in ***Figure 16***.

The control angle changes the pressure ratio between the ports and a pressure enhancement is also possible. The IHT-concept has already been tested and proven in a mobile application where four quadrant operation was required.

In order to further improve the efficiency of this innovation the floating cup principle was invented by the same company [2]. It bears the potential of use in automotive applications where huge production quantities are required. The floating cup is a rather new axial piston

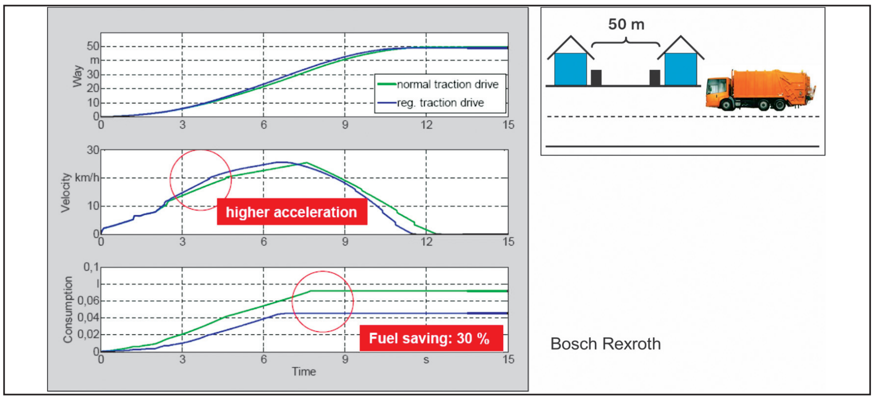

Figure 14. *Potential of performance increase and fuel savings*

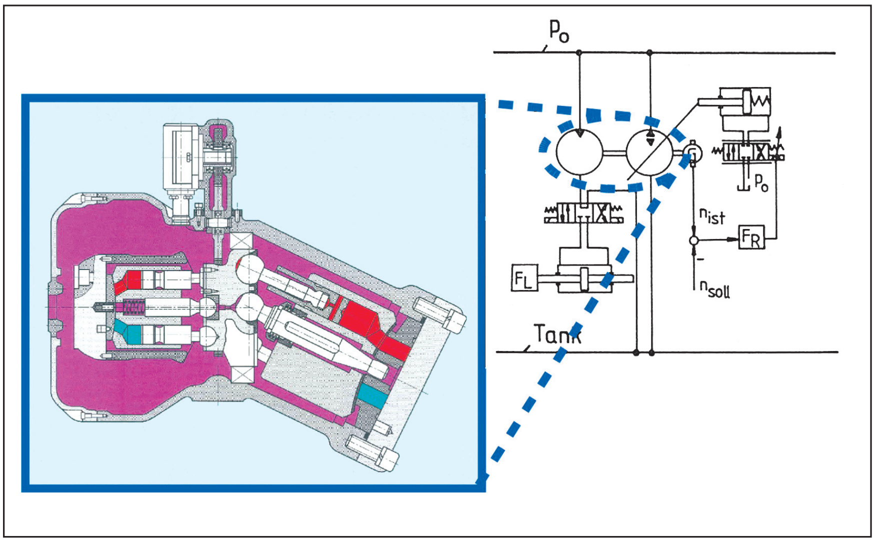

Figure 15. *Schematic and cross section of a hydraulic transformer*

machine with back to back design incorporating a large number of pistons and low friction performance. A schematic is presented in ***Figure 17***.

The max. angle of cup to piston is determined by the piston shape and the friction optimization and is in the neighbourhood of 10 %.

A design feature of the floating cup principle lies in its high amount of pistons about 3times that of conventional piston units. This significantly reduces torque ripple as measured at IFAS and Parker and shown in ***Figure 18***.

Comparing the three displacement designs a clear advantage for the floating cup principle becomes visible. This includes efficiency as well as torque variation. With this excellent performance in mind the idea was born to suggest a 'hydrid'-vehicle as depicted in ***Figure 19***.

It features permanent fourwheel drive with constant displacement floating cup motors at each wheel. The internal combustion engine drives a pump to feed the common high pressure rail. A low pressure rail ensures sufficient filling of the units. The energy control is achieved via two hydraulic transformers also using the floating cup principle. As known from electro-hybrid solutions the brake energy can be stored but without the need of two drive systems (mechanical and electrical) next to each other. The engine is decoupled from the load and the transformer allows a pressure enhancement for improved start up and acceleration torque. First simulation results of this novel concept are expected for presentation at the 6th IFK next spring in Dresden in spring 2008.

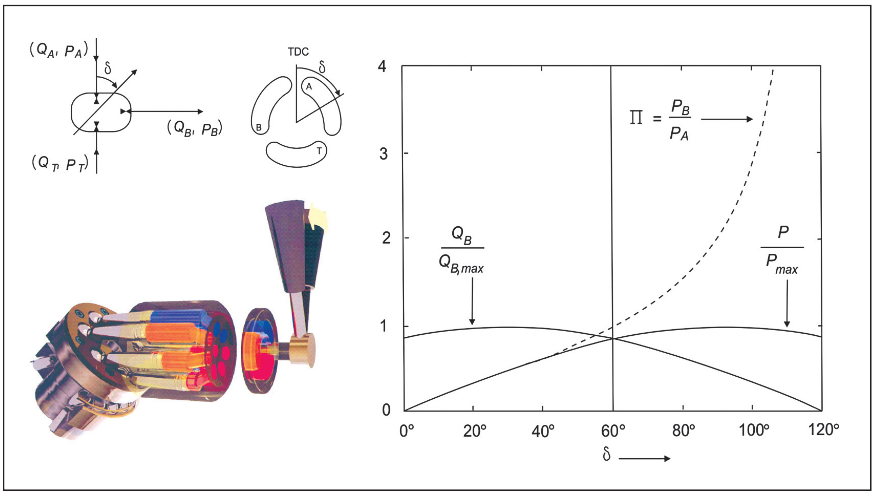

Figure 16. *Innas hydraulic transformer (IHT) and control characteristics*

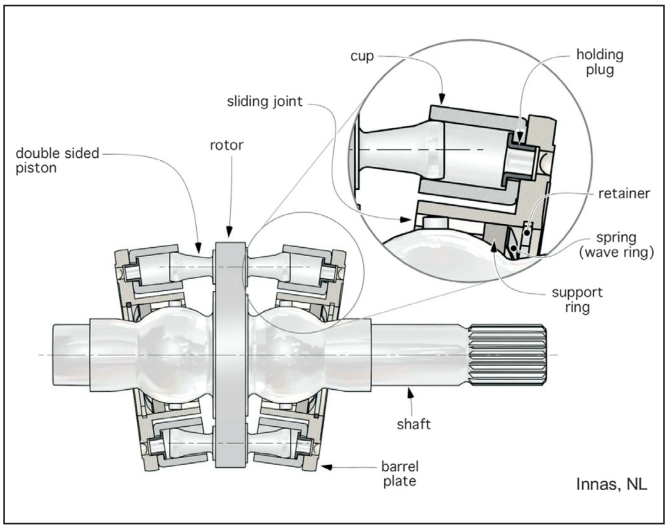

Figure 17. *Rotating parts floating cup principle*

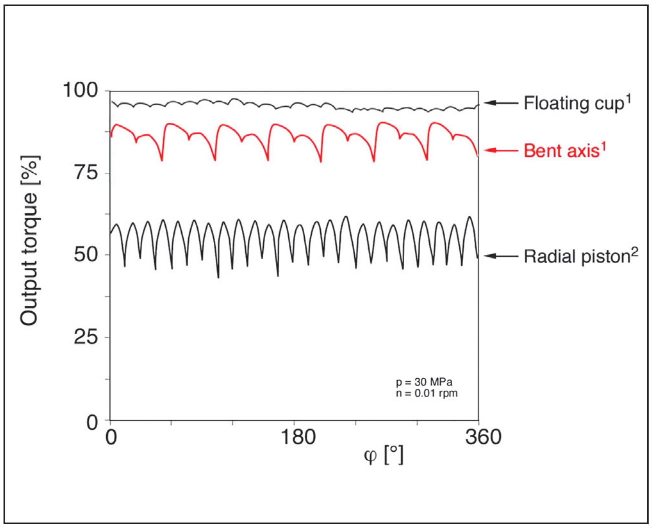

Figure 18. *Start up torque characteristics*

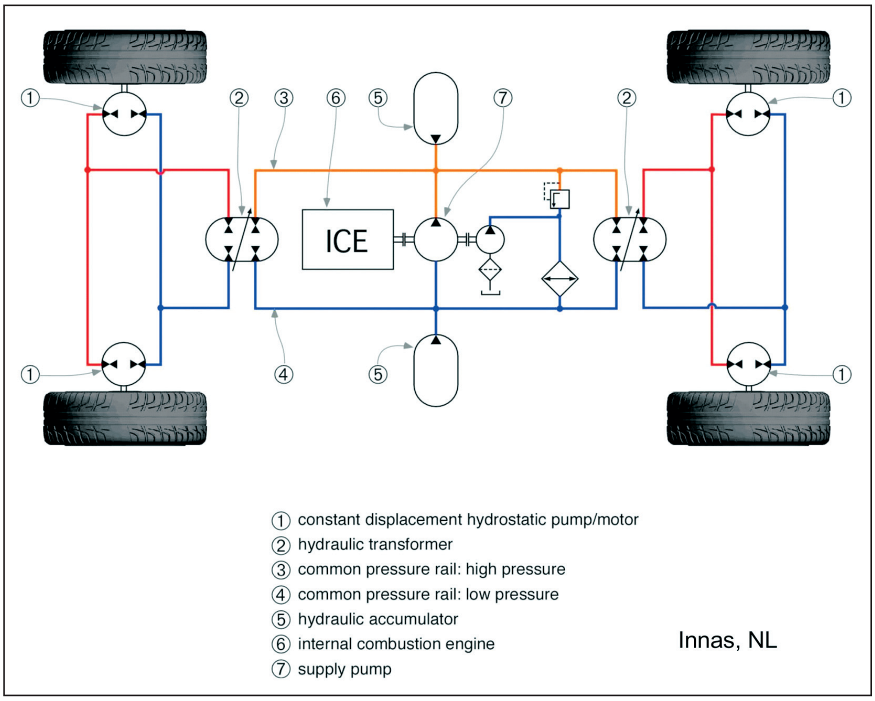

Figure 19. *Concept of a 'hydrid' vehicle drive train*

3 Work hydraulics

Distributing energy for work hydraulics in mobile equipment - not being able to use the idea of a hydraulic transformer - usually requires one pump to feed a couple of actuators. This is different to drive trains where usually one pump supports one motor in the hydrostatic transmission or a motor is used as a secondary controlled unit. For this reason load sensing systems are in use for a long time [8]. Two systems applied today are presented in ***Figure 20.*** On the left side the electro-mechanical load sensing keeps the pressure difference across the metering valve constant.

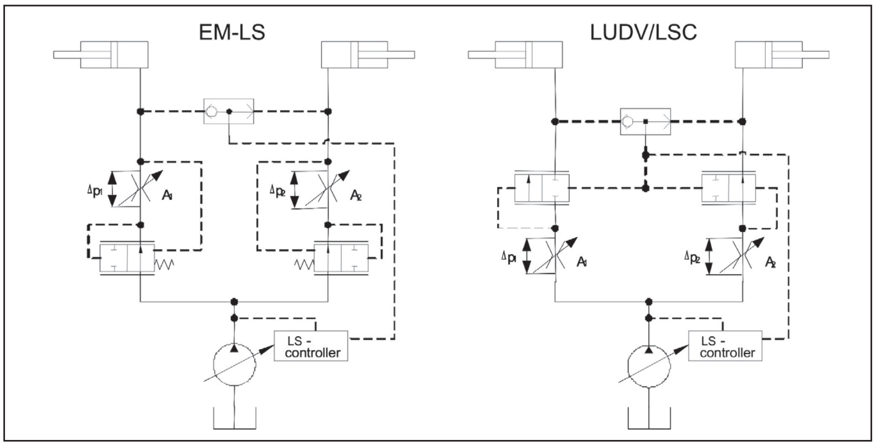

Figure 20. *Load sensing without and with flow sharing*

This is the valve connected to the joy stick of the operator. The highest load is fed back to the LS-controller of the pump keeping this pressure constant. For actuators using less pressure the individual pressure compensator is required to keep the pressure difference constant across the metering valve connected to that consumer. A problem arises in case the maximum pump flow is exceeded. In this case the highest loaded actuator slows and it can't be controlled sufficiently by the operator. For this reason a simple trick can be applied to overcome this problem by placing the metering valve upstream of the pressure compensator. The individual pressure of each consumer is compared to the maximum pressure in the system. The pressure compensator is in control position in case the same pressure acts on both sides. In case of maximum pump flow the pressure will be reduced thus also reducing the pressure differences across the metering valves leading to a proportional reduction of all flows.

An enhanced idea is presented in ***Figure 21*** called the load sensing with electronic flow matching [7]. It saves energy and at the same time improves system performance.

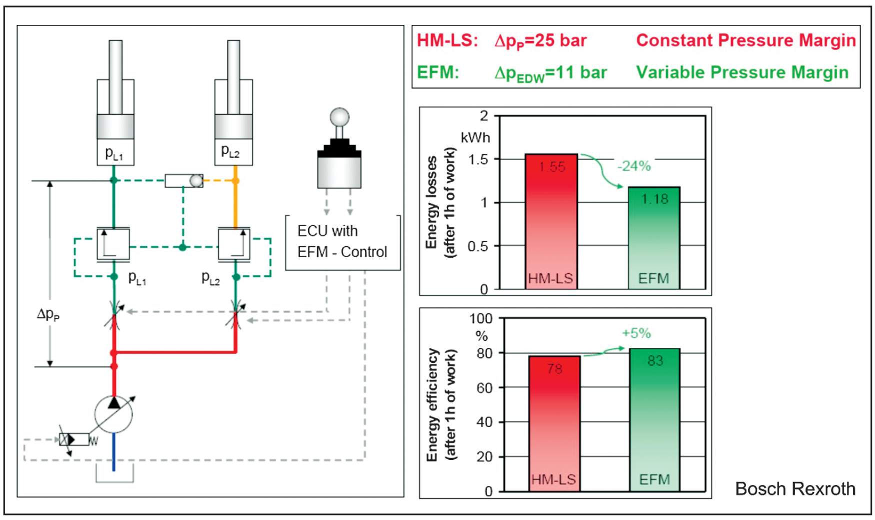

Figure 21. *Load sensing with electronic flow matching (EFM)*

The pressure controlled pump of the conventional LS-System is replaced by a purely displacement controlled unit. Displacement is governed by the flow requirements of the valves. This features the advantage that the pump doesn't have to react on load pressure changes and it operates much more robust and stable. Pump displacement

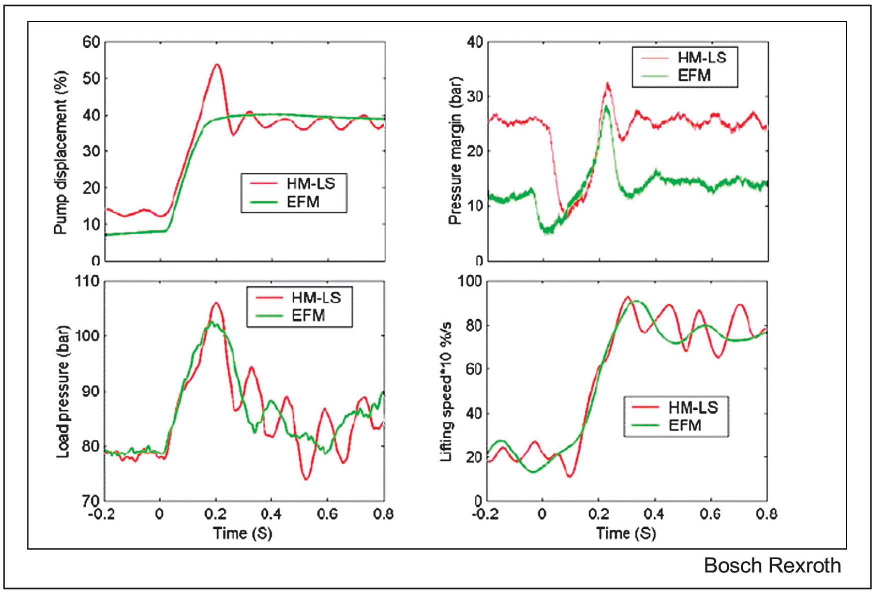

Figure 22. *Step responses comparing hydr.-mech. LS and EFM*

is time synchronous with valve opening and closing circumventing time shifts by hydraulic capacities in the circuits. Pressure losses are no longer determined by a fixed pressure difference. They are dependent on operating points and are generally lower because of decreased Δp. Real measurements performed on a tractor with a mower display a reduction in energy losses of 24 % and an increase in efficiency of 5 % compared to a conventional electro-mechanic LS-System. The achieved gain in performance is shown in ***Figure 22.***

The example contains the system of a tractor with loader in a typical cycle. Step responses of the EFM system are faster and generally display a better damping.

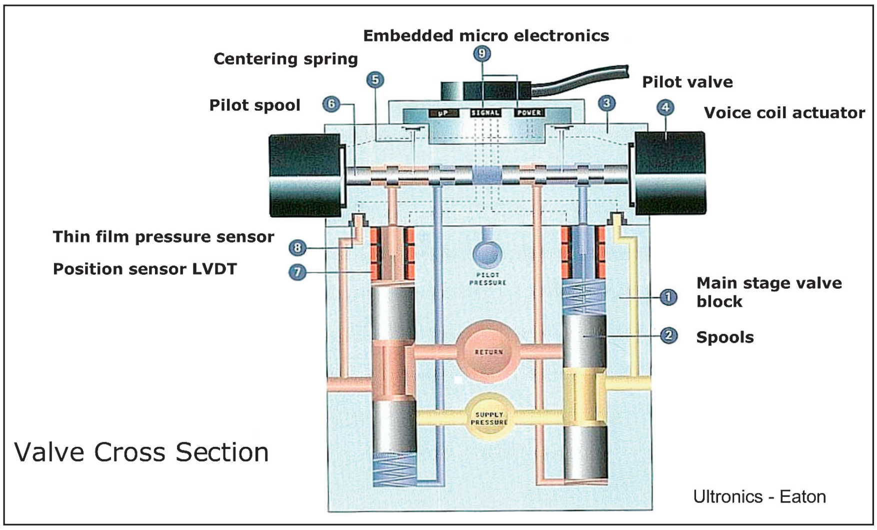

Figure 23. *Electro-hydraulic valve with integrated sensors and electronics*

Another interesting recent development is displayed in ***Figure 23*** [4]. It contains an electrohydraulic valve with integrated sensors and electronics for use in electro-hydraulic load sensing circuits.

System flexibility is increased for easy system adaptation via parameter setting. Voice coil systems control as pilots spool displacement in closed loops. Pressure and displacement sensors are integrated into the housing. An excellent dynamic performance is anticipated because of the high response voice coil actuated pilots. The highest load pressure is detected by the thin film pressure sensors and fed to the pressure controller of the pump. The system needs no pressure compensators because the flow characteristics of the spool valves are known and available for a precise flow control even at changing load conditions. The set up of the valve embedded controller is explained in ***Figure 24***. Each spool can independently be operated in pressure or flow control mode with regard to the connected cylinder chamber. The electronic control allows the implementation of additional functions compared to conventional LS-systems. It is possible to shake the bucket of an excavator for complete unloading, realise safe float, determine the load during operation or program certain machine positions. The electronic pump control provide additional degrees of freedom for components

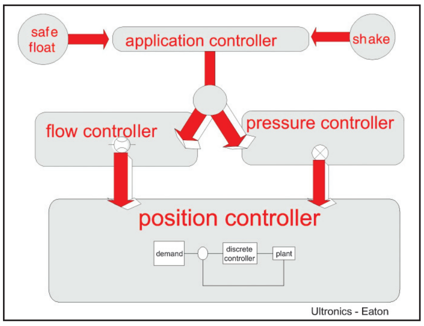

Figure 24. *Set up of the valve embedded controller*

because length of signal lines has no impact to dynamic performance.

Finally with ***Figure 25*** a set up of a controller example is depicted. The cylinder moves the excavator arm upwards using flow control on the lage piston area and pressure control on the rod side.

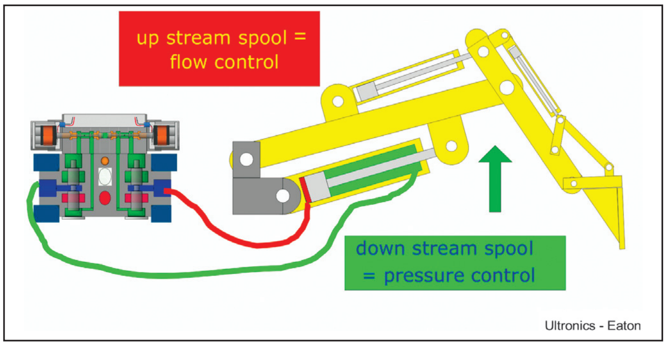

Figure 25. *Set up of a controller example for passive load*

4 Conclusion & Outlook

Focusing on the special situation for mobile hydraulics the strength of fluid power for drive train applications and work hydraulics is unbroken. However it is important to continuously improve today's solutions and generate and transform new ideas and innovations. We can see that all 4 quadrants are used today to the full benefit of the customer. Development activities are driven by energy efficiency because of rising fuel costs but as important is the growing awareness with regard to the reduction of greenhouse gases such as CO_2 contributing to global warming. It seems that a brake through in the use of regaining brake energy is close and it is worth while to bring those systems into the market to gain competitive advantage over traditional solutions. An innovative idea for a hydrid drive train solution with a new efficient floating cup displacement unit was presented and it is up to the research facilities and industry to promote these new ideas and develop those to products for mass use. We also see the increase in intelligent controls for load sensing systems in work hydraulics keeping a competitive edge for fluid power.

If we look ahead it is important to align research efforts in industry and academia with the development of alternative prime energy sources. The fuel cell might still be decades away from entering mobile hydraulic markets but one needs to be aware to react accordingly. Electric drives can store energy in batteries and super caps. Fluid power only has the equivalent to the super cap. What is missing is a high density energy storage device. Anyways, in case electric nets grow in importance on mobile machines compact, efficient and intelligent electro-hydraulic power packs are required. Some developments in aviation industry might lead us the way.

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Trendi in zadnji dosežki razvoja na področju mobilne hidravlike

Razširjeni povzetek

Hidravlični pogoni so posebej primerni za uporabo na področjih, kjer ni električnega omrežja. Tovrsten primer je področje mobilne hidravlike, kjer se za pogon uporablja motor z notranjim zgorevanjem. Ta bo v naslednjem desetletju še vedno predstavljal primarni izvor energije.

V uvodu v problematiko so najprej predstavljeni in med seboj primerjani osnovni koncepti generacije hidravlične energije. Prikazani so osnovna koncepta in značilnosti hidravličnega prenosa moči na področju stacionarne in mobilne hidravlike ter možni načini njenega krmiljenja. V ospredju obravnave je primernost uporabe pogonskega koncepta za področje mobilne hidravlike.

V nadaljevanju prispevka je prikazana problematika prenosa energije od motorja z notranjim zgorevanjem preko transmisije do koles vozila. Na podlagi delovnega diagrama klasičnega štiristopenjskega ročnega menjalnika je

prikazana prednost uporabe brezstopenjskega koncepta, ki v primeru najpogosteje uporabljanega dizelskega motorja omogoča do 12-odstotni prihranek goriva. Inštituti, ki delujejo v okviru štirih nemških univerz (RWTH Aaachen, Braunschweig, Dresden in Karlsruhe), so v sodelovanju z združenjem VDMA ustanovili raziskovalni projekt, katerega glavni namen je proučiti različne hidravlične pogonske sisteme in prenos energije na mobilnih strojih. Cilj projekta je zasnovati simulacijske modele za pogonske sisteme, ki se najpogosteje uporabljajo na omenjenem področju. Modeli pogonov upoštevajo izkoristek vseh prestav, sklopk ter hidrostatičnih enot od glavne gredi do pogonskega kolesa. Pri tem so bili podrobneje obravnavani in medsebojno primerjani izkoristki sledečih pogonskih konceptov: John Deere 6920 IVT z razdelilnikom moči, koncept več motorjev Liebherr L 544 ter koncept O&K L 25 B, pretvorba momenta s štiristopenjskim menjalnikom.

Možnost povrnitve energije, ki se sprošča ob zaviranju, je že dolgo znana prednost hidravličnega pogonskega koncepta. Koncept je bil razvit že ob energijski krizi v 80. letih, vendar je do sedaj le malo uporabnikov uvidelo serijsko uporabo tega koncepta. V prispevku sta predstavljeni dve znani možni rešitvi. Prva je primer hidrostatičnega prenosa v zaprtem krogu, kjer se energija, sproščena ob zaviranju, pošilja nazaj k črpalki, ki takrat deluje kot motor. Druga rešitev je primer sekundarno krmiljenega motorja, kjer se energija shranjuje v prigrajenem hidravličnem akumulatorju. Ena od tovrstnih sicer že četrt stoletja znanih možnih rešitev je izvedba s t. i. regenerativno pogonsko gredjo RDS, kombinacijo hidrostatične enote, ki deluje kot motor ali črpalka, in dveh hidravličnih akumulatorjev. Sistem se odlikuje po visoki dinamiki – doseganje velikih pospeškov. Podobno idejo predstavlja uporaba enote z nastavljivim volumnom, ki se lahko naknadno montira na obstoječa vozila kot dodatek. Enota se vklaplja preko prigrajene sklopke in na ta način polni oz. prazni hidravlični akumulator. S predlagano izvedbo se poveča zmogljivost vozila in občutno zmanjša poraba goriva.

Ena od prikazanih sodobnih rešitev je uporaba t. i. hidravličnega transformatorja v posodobljeni izvedbi z gibljivo skodelico (Innas). V osnovi gre za nastavljivo aksialno batno enoto s tremi priključki in trikrat večjim številom batov, kot jih ima običajna batna enota, in zaradi tega zelo zmanjšano nihanje momenta. Zadnji dosežek je uporaba tovrstne enote v obliki pogona »elektro-hydrid«.

Na področju t. i. delovne hidravlike mobilnih strojev je še vedno v ospredju uporaba sistema z zaznavanjem tlaka bremena – sistem load-sensing, ki je bil v zadnjem času deležen nekaterih izboljšav. V prispevku sta podrobneje predstavljena dva novejša dosežka na tem področju. Prvi predstavlja elektronski sistem s prilagajanjem pretoka do uporabnikov v primeru »podhranjenosti« črpalke (electronic flow matching EFM proizvajalca Bosch Rexroth), drugi pa je novi elektrohidravlični ventil z integriranimi senzorji in elektroniko proizvajalca Eaton. Zasnova ventila in elektronike omogoča večjo fleksibilnost hidravličnega krmilja zaradi prostega parametriranja elektronike in vključevanja dodatnih funkcij.

Izvleček: Hidravlični pogoni so še posebej primerni za uporabo na področjih, kjer ni električnega omrežja. Tovrsten primer je mobilna hidravlika, kjer se za pogon uporabljajo motorji z notranjim zgorevanjem. V prispevku so uvodoma predstavljene osnovne razlike, značilnosti in sistematika hidravličnega prenosa moči ter različne izvedbe pogonskega sklopa. Zaradi rastočih cen goriv, onesnaženja okolja in s tem povezanega toplogrednega učinka se ponovno oživlja ideja iz 80. let: uporaba in shranjevanje energije, ki se sprošča ob zaviranju. Na to temo je predstavljenih nekaj sodobnih rešitev in izboljšav, ki omogočajo višji izkoristek in zmogljivost tovrstnih pogonov. Drugi del prispevka obravnava distribucijo hidravlične energije iz enega vira, običajno regulirane črpalke, ki jo poganja motor z notranjim zgorevanjem, do posameznih gradnikov delovne hidravlike. Podrobneje je predstavljen elektrohidravlični load-sensing koncept. Prispevek je bil predstavljen na srečanju Fluidna tehnika 2007 v Mariboru in je razširjena verzija krajše predstavitve na kongresu The Future of Power Transmission (maj 2007, Italija).

Ključne besede: hidravlični pogoni, mobilna hidravlika, pogonski koncepti, izvedbe,

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– Nova področja uporabe fluidne tehnike (medicinska tehnika, vodna hidravlika, tehnika preskušanja ...)
– Varnost, razpoložljivost in okoljska primernost
– Teoretične osnove in demonstracijske tehnike.

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