

SAVING THE WORLD'S ENERGY WITH FLUID POWER

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ABSTRACT

Fluid power transmits a surprisingly large amount of energy with remarkably low efficiency, providing an extraordinary opportunity to save energy, save money, improve the environment and create new businesses using more efficient fluid power technology. In this paper we will describe how new fluid power components and systems can significantly improve efficiency by creating more efficient systems and by improving the efficiency of individual components. This paper describes three applications; an excavator, a hydraulic hybrid vehicle, and a wind power generator; to demonstrate how fluid power saves energy in a cost effective way. In the excavator, elimination of throttling and regeneration can more than double fuel efficiency. Hydraulic hybrid vehicles are now entering the market where they are superior to electric hybrid vehicles for heavy applications such as refuse trucks and delivery vans. With improved technology, hydraulic hybrids could overtake electric hybrids as a cost-effective but efficient passenger vehicle. Wind is a rapidly growing power source, with the Department of Energy leading an effort to provide 20% of U.S. electricity from wind by 2030. Hydrostatic drives could replace mechanical gear boxes, extracting more power with higher reliability.

KEYWORDS

Efficiency, fluid power, excavator, hydraulic hybrid vehicle, wind power

INTRODUCTION

In 2010, Oak Ridge National Laboratory (ORNL) teamed with the National Fluid Power Association (NFPA) and with eighteen industry partners to quantify the impact of fluid power on the U.S. energy consumption [30]. The report on the study is still in draft form, but should be approved and published soon. The initiative for this study came from Lonnie Love of Oak Ridge National Laboratories, a member of the Center for Compact and Efficient Fluid Power (CCEFP) Scientific Advisory Board. The study was

conducted by Eric Lanke and Pete Alles of NFPA. The goal was to quantify the amount of energy transmitted using fluid (hydraulics and pneumatics) and to predict potential energy savings from advancing fluid power technology. The study shows that there is a great potential to save energy in both industrial and mobile applications by using more efficient fluid power components and systems.

In 2008, fluid power systems transmitted 2.3 to 3.0 per cent of energy in the U.S.A. To put this in perspective, the U.S. consumes approximately 100 Quads (1 Quad

is 10^{15} BTUs) of energy annually, with each Quad costing \$20B if it is derived from petroleum. Since the U.S.A. represents approximately one third of the world's economy, the worldwide transmission of energy via fluid power is around 7 to 9 Quads valued at \$14 to \$18 billion or more that one trillion yen.

Moreover, the study revealed that fluid power systems are remarkably inefficient with efficiencies ranging from 6% to 40%, depending upon the application, with an average efficiency of 21%. The largest fluid power energy uses were mobile hydraulics and industrial pneumatics with the hydraulics typically being more efficient than the pneumatics. The large amount of energy used and the inefficiency of current systems make it clear that investing in more efficient hydraulics and pneumatics can reap significant savings in overall energy use.

A survey of the participating fluid power manufacturers predicts that a 5% improvement in efficiency is easily achievable with best practices over the next five years. This near term objective could consumers and industry over \$9 to \$11 billion per year in energy costs and reducing emissions by over 33 million metric tons of CO₂ per year. A longer term goal, through a strategic R&D program focusing on new controls, manufacturing and materials, could result in a 15% improvement in efficiency over the next fifteen years. Realizing this ambitious goal could save industry and consumers more than \$19 to \$25 billion per year in energy costs and reducing emissions by more than 90 million metric tons of CO₂ per year. Just as important, an ambitious program to develop energy efficient fluid power could invigorate the fluid power industry increasing our manufacturing capabilities and competitiveness in the growing world market.

In making these projections, it is important to note that we are considering current applications only. The expansion of fluid power into new applications can significantly increase the impact on energy savings, sustainability and economic development. Examples of new markets with significant energy savings are hydraulic hybrid vehicles and wind power transmission using hydrostatic transmissions.

TOWARD MORE COMPACT AND EFFICIENT COMPONENTS AND SYSTEMS

The Center for Compact and Efficient Fluid Power (CCEFP) [1-3, 31, 32] is conducting research aimed at significant energy savings. The CCEFP has four goals. The first goal is to dramatically improve the energy efficiency of fluid power in current applications; the second goal is to improve the efficiency of the transportation sector by developing fuel efficient hydraulic hybrid passenger vehicles; the third goal is to develop un-tethered portable human-scale fluid power devices; and the fourth goal is to make fluid power more acceptable and ubiquitous. Thus the first and second goals are explicitly addressing the energy issue.

Figure 1, below, shows power and weight of the CCEFP test beds. These test beds; medical devices, robots, passenger vehicles, excavators and wind turbines; are carefully chosen to span the range of power and weight of interest. Note that the plot uses log-log scales so that the range of power and weight considered spans many orders of magnitude. The most significant energy savings can be realized in the larger systems; the hydraulic hybrid passenger car, excavator and wind turbine. Improving the efficiency of these systems will have a very large impact on overall energy consumption of the economy. The smaller systems; the robot and medical devices; will not save significant amounts of energy when compared to the overall energy consumption of the economy, but energy efficiency is very important for improving the performance of smaller systems. In the next sections, some details are provided on ways to increase the efficiency of the three largest test beds, the energy efficient excavator, hydraulic hybrid passenger vehicle and hydrostatic transmission for wind power. Due to space limitation, emphasis will be put on CCEFP research activities recognizing that many others around the world are making important contributions toward making more efficient fluid power systems.

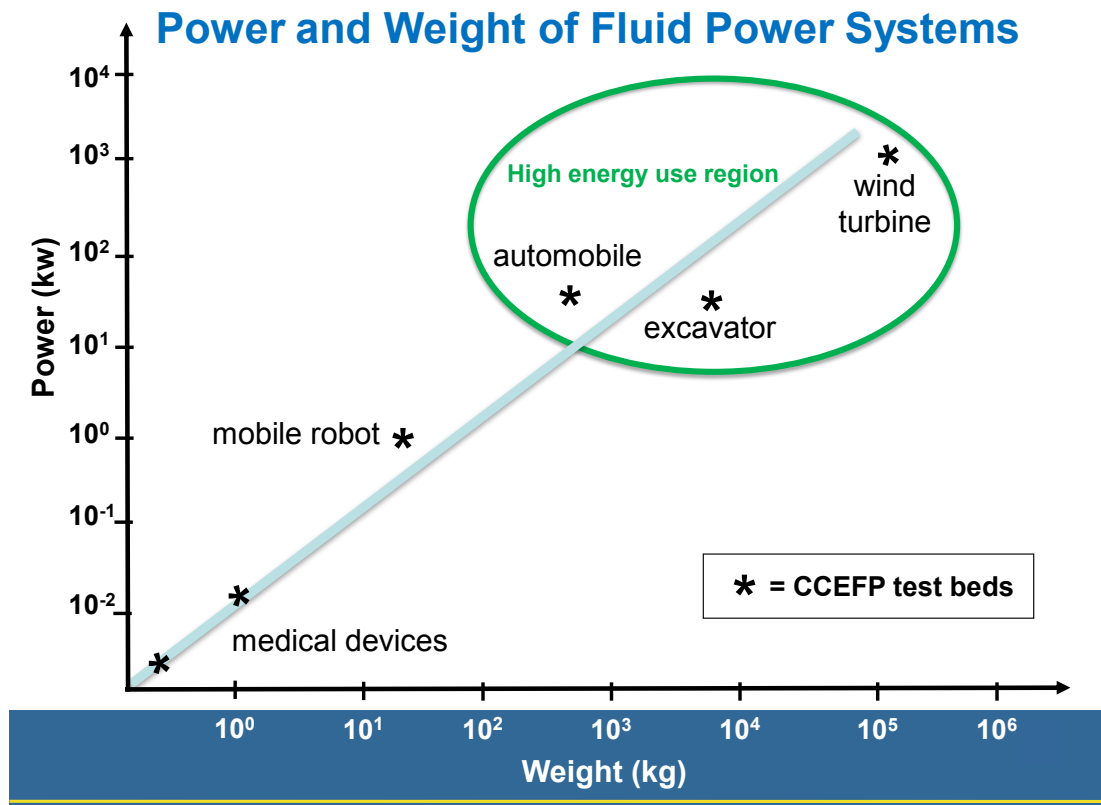


Figure 1: Power and Weight of Fluid Power Systems

ENERGY EFFICIENT EXCAVATOR

As an example of current application of fluid power in mobile hydraulics, consider the excavator. Excavators are important in their own right, but are also representative of off-road hydraulic applications more generally, with separate propel, steering and multiple work circuits that are used intermittently. Thus, approaches to making excavators more efficient have potential to be applied to other classes of machines.

An energy audit of a excavator executing typical dig cycles shows that over 40% of the energy is lost in the throttling valves with no possibility of recovery. Displacement control [43, 44, 45, 46] eliminates the dissipation from throttling by replacing control valves with variable displacement pumps. Displacement controlled actuation is reversible, allowing energy from one work circuit to be used to drive another work circuit instantaneously. With the addition of energy storage in an accumulator, even more energy can be saved.

The experimental displacement controlled mini excavator at Purdue has been independently tested at Caterpillar. The predicted reduction in fuel

consumption of nearly one-half has been verified. Further, increases in digging productivity mean that the energy per unit earth moved, a more meaningful measure of efficiency, was reduced by more than half. The improvement in excavator efficiency has other benefits, notably the possibility of eliminating the cooling circuit [48]. With the transition from valve control to pump control, improving the efficiency of pumps with careful attention to all of the physical causes of loss becomes increasingly important [17]. Further improvements in efficiency can also be realized by carefully tailoring the hydraulic fluid to the application where high viscosity index fluids can increase efficiency by reducing the temperature sensitivity of the viscosity [16].

An alternative to controlling fluid power using throttling valves is to control fluid power using high speed on-off valves, sometimes called digital valves. The idea is to control the flow by rapidly opening and closing the valve. Since ideally the valve is very efficient in the fully open or fully closed state, a very efficient control is created, with most of the dissipation occurring during transitions. The improvement in efficiency is analogous to the improvement in the efficiency of lighting control when rheostats were

replace by silicon controlled rectifiers (SCRs) enabling much more efficient control. Research of high-speed on off valves is using two approaches, a rotary valve [27, 28, 34, 40] and high speed poppet valves [5]. The development of high-speed on-off valves can also lead to digital pumps or pump-motors, an approach that promises to have broad applicability especially for vehicle applications where four-quadrant operation is needed [22, 23, 29, 41].

A promising but often overlooked opportunity to improve excavator efficiency is in developing more efficient and effective human-machine interfaces [10-15, 21]. Improved human-machine interfaces can improve productivity since getting a job done faster means less fuel will be used. Better human-machine interfaces have the added advantage of decreasing operator fatigue, reducing the frequency of mistakes and increasing safety. Machine characteristics play an important role in user interface design. For example, the replacement of throttling controls with displacement controls creates a machine with different dynamics. This change, if not properly understood and dealt with, can lead to instability, a situation that has recently been addressed by CCEFP researchers [38, 39, 45].

HYDRAULIC HYBRID PASSENGER VEHICLE

Since transportation uses about one third of our energy, improvement in transportation have an important effect on overall energy use. Hydraulic hybrid vehicles have been demonstrated to have greater efficiency and lower costs than electric hybrid vehicles in heavier applications such as refuse trucks and city buses. As an example of their expanding application, New York City is in the process of purchasing three hundred hydraulic hybrid refuse trucks.

The hydraulic hybrid passenger car is an example of a new application of fluid power. Hydraulic hybrid vehicles are clearly superior for larger sizes, and efficient and cost-effective solutions are currently coming on the market. The situation is more equal in the passenger vehicles, with several recent studies showing that hydraulic hybrid vehicles are competitive with electric hybrid vehicles [18, 37]. Crucial to the comparison is the efficiency of pumps and pump-motors, with future improvements in high-efficiency digital pumps and pump-motors tipping the balance in favor of hydraulic hybrid approaches. A recently between the U. S. Environmental Protection Agency (EPA) and Chrysler Corporation to develop a prototype Town and Country minivan hydraulic hybrid vehicle shows the commercial interest in migrating hydraulic hybrid approaches to the smaller passenger vehicle market.

There are four common hydraulic hybrid configurations, parallel, series, input coupled hydro-mechanical and output coupled hydro-mechanical, where hydro-mechanical transmissions are also called power-split transmissions. The parallel configuration is the simplest form where a hydraulic regenerative unit is added to a conventional mechanical power train. Parallel hydraulic vehicles have high transmission efficiency, but poorer engine management, limiting efficiency. Series hydraulic hybrid vehicles replace the mechanical transmission with a hydrostatic transmission. Since a hydrostatic transmission is continuously variable, the series configuration has better engine management than the parallel configuration, but losses in the hydrostatic transmission can be greater than the gain in engine efficiency. This is the reason that efficient pumps and pump-motors are needed to improve series hydraulic hybrid vehicles. Of the vehicles just coming on the market, parallel configurations are favored for the refuse truck application, while series configurations are favored for the delivery van application.

A hydro-mechanical or power-split transmission is an attractive alternative to the parallel or series configurations where these transmissions can be of the input coupled or output coupled type [6, 36, 42]. Hydro-mechanical transmissions have two power transmission paths, a mechanical path and a hydraulic path. Hydro-mechanical hybrid hydraulic vehicles can potentially have better fuel economy than either the parallel or the series configuration since can be both efficient and continuously variable.

Comparisons between hybrid vehicle concepts depend on many factors including component performance and sizing, duty cycle and control approach [19]. This makes valid comparisons difficult. Control based on dynamic programming is often assumed in comparative studies since it produces the optimum result theoretically, but dynamic programming cannot be used in practice because it requires future information [25, 33]. Real time control approaches that can prove effective are stochastic dynamic programming [24, 26] and model predictive control [7-9]. A three level decomposition with a Lagrange multiplier formulation has proven to be effective for the control of hydro-mechanical hydraulic hybrid vehicles [20].

HYDROSTATIC TRANSMISSION FOR WIND TURBINE

Wind power will become an increasing important renewable source of electricity in the future with the United States Department of Energy (DOE) setting the goal of receiving 20% of our electricity from wind by

2030 [4]. Since the electrical generator must turn much faster than the blades of the turbine, wind power generators require a speed-up transmission. The current approach is to use a fixed ratio mechanical gearbox, but mechanical gearboxes are heavy, costly and unreliable. The unreliability is caused by fatigue from the multi-axis dynamic loading of the wind.

Hydrostatic transmissions provide an attractive alternative to mechanical gear boxes for wind power [35]. Hydrostatic transmissions are lighter and cheaper than gear boxes and can be made more reliable than gear boxes by using hydrostatic bearings to avoid fatigue. Although hydrostatic transmissions are less efficient than gear boxes their use can cause higher overall efficiency since the variable ratio can be used to increase the aerodynamic efficiency of the rotor. The variable ratio also allows the use of a synchronous generator, eliminating the cost and inefficiency of power electronics. The hydrostatic transmission also has a cushioning effect that increases generator life by isolating the generator from shock loading of the wind. One novel approach is to split the hydrostatic transmission with the pump located in the nacelle but the hydraulic motor located at ground level along with the generator and controller. This approach reduces the weight in the nacelle and allows easy ground level access to all major components for maintenance, repair or replacement.

CONCLUSION

A recent survey has revealed that fluid power transmits large amounts of energy with low efficiency, providing an attractive opportunity to save energy, save money, improve the environment and create new businesses using more efficient fluid power technology. We have shown how significant efficiency improvements can be obtained for three examples, an energy efficient excavator, hydraulic hybrid passenger car and hydrostatic transmission for wind power. Efficiency improvements can come for more efficient components such as pumps and valves, but also from improved fluids. System architectures, controls and operator interfaces can also play a significant role in improving system efficiency.

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