INTERNATIONAL JOURNAL OF FLUID POWER
2018, VOL. 19, NO. 2, 69–79
https://doi.org/10.1080/14399776.2017.1386061

A review of hydro-pneumatic and flywheel energy storage for hydraulic systems

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ABSTRACT

This review will consider the state-of-the art in the storage of mechanical energy for hydraulic systems. It will begin by considering the traditional energy storage device, the hydro-pneumatic accumulator. Recent advances in the design of the hydraulic accumulator, as well as proposed novel architectures will be discussed. The review will continue with a discussion of energy storage flywheels. This will include recent advances in flywheel design and the properties of flywheels, particularly when compared to accumulators, as applied to hydraulic systems. These differences necessitate a discussion of the hydraulic system architectures used to incorporate flywheels, which will cover the various methods that have been proposed for utilising energy storage flywheels in hydraulic systems. The review will conclude by highlighting some of the unanswered questions in this area of engineering research and design.

ARTICLE HISTORY
Received 18 July 2016
Accepted 26 September 2017

KEYWORDS
Hydraulic energy storage; accumulator; flywheel; hybrid energy storage; hydro-mechanical hybrid storage

Introduction

Hydraulics are widely used in industries where a high power-to-weight ratio or durability is paramount. It is the power transmission system of choice in the agriculture, mining and construction industries (Love *et al.* 2012). The potential for energy recovery in hydraulic systems has long been recognised (Pourmovahed *et al.* 1992a, 1992b) and has proven its potential to increase the efficiency of systems ranging from construction equipment (Caterpillar 2013) to on-road vehicles (Alson *et al.* 2004, Altair 2011). At times the recovered energy can be directed to another load on the system, thereby reducing engine power or unloading the engine completely. At other times, the recovered power exceeds the demand of the other loads on the system. In these cases, the recovered power must either be stored or dissipated. In general, storage allows a highly variable demand to appear, to the prime mover, as constant, or at least closer to constant, allowing the engine to run at a more constant power and often at a more efficient operating point. The purpose of this paper is to review the state-of-the art in mechanical energy storage methods for hydraulic systems. While it is possible for a hydraulic system to use electrical or chemical energy storage, this review is focused on mechanical energy storage, specifically potential and kinetic energy storage. The energy storage systems of focus are hydraulic accumulators and flywheels, with consideration of their performance characteristics and an examination of the various methods that have been proposed for employing flywheels in hydraulic systems. This study focuses on the most important performance metrics of modern hydraulic energy storage devices, especially as applied to mobile systems, which are their efficiency and specific energy.

This paper will review modern hydro-pneumatic accumulators, including their energy loss mechanisms and recent advances in their design. This will be followed by an overview of modern energy storage flywheel technology, including recent research and commercial developments. Then a comparison of these two types of storage will examine how their principles of operation effect their application to hydraulic circuits. Finally, the various methods that have been proposed for applying energy storage flywheels to hydraulic circuits will be reviewed. The paper will conclude with an examination of the questions and problems remaining in the application of energy storage flywheels to hydraulic systems.

Accumulators

The most common and technologically mature method of storing energy in hydraulic systems is the accumulator. This device converts hydraulic power into potential energy. This potential energy can be a compressed gas, a strained elastic material, a compressed metal spring or a lifted weight. Gas-charged accumulators are the most common, and include several architectures that differ in the method of separating the pressurised gas from the hydraulic fluid, using either a piston, diaphragm or bladder.

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Energy losses

The main energy loss mechanism in gas-charged accumulators is heat transfer from the accumulator. If the gas is not compressed slowly, which is seldom practical, the temperature rises. Although this general behaviour can be described by the ideal gas law, the behaviour of most gases, including nitrogen, diverges from that of an ideal gas at the higher pressures typical of hydraulic systems. At these pressures, the behaviour is more accurately described with the Benedict–Webb–Rubin equation (Pourmovahed 1988). This heat generated by compressing the gas is convected to the walls of the accumulator and lost to the environment. During re-expansion of the gas, the inverse happens and the gas temperature drops. If this process is not performed slowly enough for heat to be absorbed from the environment, the result is significantly less energy extracted from the gas than was initially added.

Much study has concentrated on modelling and mitigating this thermal energy loss. Pourmovahed and Otis generated a model that describes the overall thermal behaviour of the accumulator using a thermal time constant that depends on the gas and the construction and orientation of the accumulator (Pourmovahed and Otis 1990). Pourmovahed et al. then went on to study methods to mitigate this deficiency. They found that filling the gas portion of the accumulator with elastomeric foam could reduce the thermal losses in an accumulator from 10 to 20% to as low as 1% (Pourmovahed *et al.* 1988). They also tested the durability of this foam and found it appropriate for this application (Pourmovahed 1990).

Other energy losses in a hydro-pneumatic accumulator include friction (in the case of a piston accumulator) or hysteresis (in the case of a bladder or diaphragm accumulator) and the flow loss at the accumulator port. Pourmovahed et al. experimentally observed that these energy losses account for 1 to 5.5% of total energy input to the accumulator (Pourmovahed *et al.* 1988). This rich body of work has led to modern accumulators which can exhibit round trip efficiencies as high 95% (Pourmovahed *et al.* 1988).

Composite materials

Accumulators have also benefitted significantly from application of advanced composites. The stress on the shell of a pressurised accumulator lends itself to the anisotropic nature of glass and carbon fibre composites. Several companies, such as Parker Hannafin (2016) and Steelhead Composites (2015), offer composite accumulators, and the mass reduction over steel accumulators is significant and scales with accumulator size (Mallick 2015).

Researchers at the EPA proposed and constructed composite accumulators even lighter than those commercially available. This team also researched accumulator bladder material that prevents nitrogen permeation in order to limit the routine maintenance required to bleed nitrogen from the hydraulic fluid of a closed circuit (Alson *et al.* 2004).

Alternate accumulator technologies

Two primary limitations plague hydro-pneumatic accumulators. First, the specific energy is quite low, approximately two orders of magnitude lower than advanced chemical batteries (Van de Ven 2009). Second, the pressure in a hydro-pneumatic accumulator decreases logarithmically with the state of charge. This effect requires higher flow rates at lower states of charge, resulting in larger and heavier components in the rest of the system compared to operating at a constant pressure. Several other accumulator technologies have been presented as means to overcome these weaknesses, as well as the problem of permeation of gas through the gas-oil separator.

The open accumulator proposed by Li et al., is a gas-charged accumulator to which energy can be added and retrieved by either adding or removing hydraulic fluid or changing the mass of pressurised gas through the use of a pneumatic compressor/motor. The concept has both the potential to increase the specific energy by an order of magnitude over traditional accumulators and the ability to uncouple the system pressure from the storage unit state of charge (Li *et al.* 2007). Much of the study of the open accumulator has focused on its application to large, stationary applications, such as grid energy storage for offshore wind turbines (Li *et al.* 2011). Recent promising advances toward implementation of the open accumulator have focused on the development of an efficient pneumatic compressor/motor (Saadat and Li 2015, Yan *et al.* 2015).

The variable area accumulator proposed by Van de Ven presents a method of constructing gas-charged hydraulic accumulators to control the relationship between pressure on the gas and liquid sides of the accumulator. The design is applicable to piston style accumulators and uses a uniquely shaped piston and a rolling diaphragm seal to create a surface area on the gas side of the piston that is different from that on the oil side and that varies with piston position. This allows the oil side of the accumulator to experience a constant pressure while the gas side pressure increases, providing a constant oil pressure as the energy stored in the compressed gas increases. The concept offers the potential to increase specific energy over traditional piston accumulators, while mitigating the hydraulic system pressure dependence on state of charge. Implementation of this design requires further research in the design and manufacture of high-pressure rolling diaphragm seals (Van de Ven 2013).

The strain energy accumulator proposed by Barth et al. stores energy in a strained solid rather than in a compressed gas. This design is promising due to the high-energy density and specific energy of highly strained elastic materials. The design also mitigates the previously discussed heat transfer problem of compressed gas accumulators and does not suffer from the problems caused by gas permeation past bladders or seals. The concept has the potential to double or triple the specific energy over traditional accumulators (Pedchenko and Barth 2009). The design consists of an elastic bladder, which strains as fluid is added, and a protective shell to prevent failure of the bladder (Barth *et al.* 2014). Prototype strain energy accumulators have been constructed and tested at moderate pressures and currently present challenges in clamping the highly strained elastic material (Tucker and Barth 2013, Cummins *et al.* 2014).

Flywheels

An alternative to storing hydraulic energy in a hydro-pneumatic accumulator is to store it kinetically in a flywheel driven by a hydraulic pump/motor. In some applications, the increased complexity and energy loss added through the inclusion of the hydraulic pump/motor are warranted due to the flywheel's increased specific energy and energy density. This section will discuss modern advances in flywheel energy storage, compare the characteristics of accumulators and flywheels when applied to hydraulic systems, and finally review the various hydraulic circuits that have been proposed for flywheel energy storage.

Similar to accumulators, flywheel technology also has a rich history, much of which was described by Genta (1985) in his 1985 review of flywheel design, construction and support systems. The kinetic energy stored in a flywheel is a function of the flywheel inertia and angular velocity. Since flywheel mass increases with inertia, faster flywheels are preferred for applications in which lower system mass is desired.

The primary challenges highlighted by Genta were the radial stress experienced by flywheels, which poses a difficulty for anisotropic composite materials, and the interface between the flywheel and the shaft that supports it. Both of these problems have been the subject of recent study and significant advances have been made.

Recent advances

Ha et al. studied flywheel designs consisting of multiple composite shells coupled with an interference fit in order to pre-stress the composite in compression. The team discovered optimal dimensions for such a design (Ha *et al.* 2001) and discovered that the resulting designs could be scaled (Ha *et al.* 2008, Janse Van Rensburg *et al.* 2013). They also developed and modelled designs for split-type hubs (Ha *et al.* 2006) and composite hubs (Kim *et al.* 2014), the latter of which has also been the subject of several patents (Bakholdin *et al.* 1996, Spears *et al.* 2010). These studies have been accompanied by the manufacture (Ha *et al.* 2008) and testing of the resulting designs (Hayat *et al.* 2006), validating the findings.

Flywheel support systems have also seen significant advances since the publication of Genta's book. Energy storage flywheels are usually contained in a vacuum chamber to reduce the aerodynamic energy losses. Recent advances in magnetic gears allow torque transfer through the walls of this chamber without the use of shaft seals and their associated friction and vacuum leakage (Jian *et al.* 2009). Magnetic bearings (Bleuler *et al.* 2009) have been applied to stationary flywheels and offer significantly reduced friction over traditional rolling element bearings (Strasik *et al.* 2007, 2010). Even rolling element bearings have seen improvements since Genta's publication, with the use of composite and hybrid bearings, which offer more modest reductions in bearing friction (Stoneburner and Technologies 2005, GMN 2014).

Commercial application

The result of flywheel research to date has been an increase in the number and performance of commercial production and prototype flywheels. In 2011, Hansen and O'Kain produced an Oak Ridge National Laboratory report describing the state-of-the art in flywheel technology as applied to mobile applications (Hansen and O'Kain 2011). A prominent example of mobile flywheels in hydraulic applications is the Ricardo hybrid excavator, which uses an energy storage flywheel to recover energy in the operation of the excavator boom (Ricardo 2014). The Ricardo prototype also makes use of a novel magnetic gear design (Atkins *et al.* 2016) with promising performance (Hansen and O'Kain 2011).

Perhaps the most well-known examples of mobile flywheel energy storage are designs developed for use in Formula 1 Racing. Flybrid, Ricardo, and Williams Hybrid Power have all developed such systems. The flywheels for this application have been subjected to extensive testing, including more than 75 million revolutions, 5000 miles of vehicle driving and a crash test of more than 20 g, proving that modern flywheel technology is sufficiently rugged for vehicle applications (Hansen and O'Kain 2011). The design is therefore being considered for use in production Volvo passenger cars (Volvo Car UK 2014).

Energy losses

There are two types of energy losses in a flywheel energy storage system, those in effect when power is flowing into or out of the flywheel and those in effect at all times. A clutch is usually used to limit the losses in the flywheel when it is idling. This has been shown experimentally

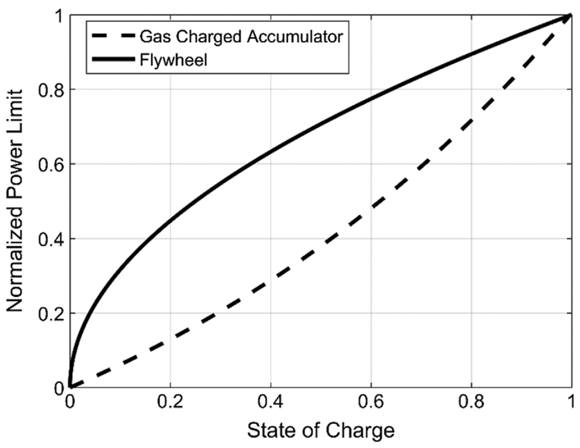

Figure 1. The dependence of normalised power limite on state of charge for flywheels and accumulators, for an example, accumulator.

to significantly reduce the idling losses of a flywheel, and will be discussed in more detail below (Shimoyama *et al.* 2010). When this clutch is disengaged, the losses are limited to aerodynamic friction and bearing friction. When the clutch is engaged, additional losses are incurred, including those in the pump/motor unit, the shaft seals (FerroTech n.d.) or magnetic gears (Jian *et al.* 2009) and any gearing or transmission.

Differences between flywheels and accumulators

The differences between accumulators and energy storage flywheels applied to hydraulic applications can be best highlighted by comparing the behaviour of an ideal flywheel coupled to a pump/motor to an ideal traditional accumulator. The traditional accumulator exhibits a state-of-charge-dependent pressure while its flow capability, at least for an ideal accumulator, remains constant. The energy in an accumulator charged with ideal gas operating isothermally is:

$$\boldsymbol{E}_{\mathrm{acc}} = \boldsymbol{P}_{ch}\boldsymbol{V}_{ch}\ln\left(\frac{\boldsymbol{P}_s}{\boldsymbol{P}_{ch}}\right) \quad \text{or} \quad \boldsymbol{P}_s = \boldsymbol{P}_{ch}\boldsymbol{e}^{\left(\frac{E_{\mathrm{acc}}}{P_{ch}V_{ch}}\right)} \tag{1}$$

where P_{ch} and V_{ch} are the gas pressure and gas volume, respectively, at pre-charge, P_s is the oil pressure and E_{acc} is the energy stored in the accumulator. Any hydraulic circuit component has a maximum flow rate, which, for example, is based on a hydraulic motor's full displacement and rated speed or the cross-sectional area and maximum velocity of a linear actuator. For this given maximum component flow rate, the proportion of rated power, $\frac{W_{\mathrm{acc}}}{W_{\max}}$, that the accumulator can provide is:

$$\frac{\boldsymbol{W}_{\mathrm{acc}}}{\boldsymbol{W}_{\max}} = \frac{\boldsymbol{P}_{\mathrm{acc}}}{\boldsymbol{P}_{\max}} = \boldsymbol{e}^{\frac{E_{\mathrm{acc}}-E_{\mathrm{acc,max}}}{P_{ch}V_{ch}}} \tag{2}$$

where $P_{\max}$ is the rated system pressure and $E_{\max}$ is the energy stored in the accumulator at rated system pressure. The ideal flywheel and its pump-motor, on the other hand, can provide rated system pressure regardless of its state-of-charge but exhibits a state-of-charge-dependent flow limit. The energy stored in the flywheel, E_{fw}, is:

$$\boldsymbol{E}_{fw} = \frac{1}{2}\boldsymbol{I}_{fw}\boldsymbol{\omega}_{fw}^2 \tag{3}$$

where I_{fw} is the flywheel inertia and $\boldsymbol{\omega}_{fw}$ is the flywheel speed. This means that, for a given rated system pressure, the proportion of rated power, $\frac{W_{fw}}{W_{\max}}$, that the flywheel and pump/motor can provide is:

$$\frac{\boldsymbol{W}_{fw}}{\boldsymbol{W}_{\max}} = \frac{\boldsymbol{\omega}_{fw}}{\boldsymbol{\omega}_{\max}} = \sqrt{\frac{\boldsymbol{E}_{fw}}{\boldsymbol{E}_{fw,\max}}} \tag{4}$$

These normalised power limits, for the accumulator and flywheel-pump/motor, Figure 1, show the flywheel-pump/motor can provide higher normalised power at all but full state of charge. This plot depicts an accumulator of arbitrary size and pre-charge pressure for the purposes of illustration, however, due to the presence of the logarithmic function in Equation (1) and the square root in Equation (4), ideal flywheels will always exhibit rated power levels which decrease less rapidly with state of charge than those of ideal accumulators. This behaviour should not be confused with the maximum power that the two storage devices can provide. The flywheel-pump/motor has a clear maximum power limit defined by the rated pressure of the system components, rated flywheel speed and maximum pump/motor displacement. While the power limit of these systems can be increased by specifying large hydraulic pump/motors and higher speed flywheels, these changes accompany trade-offs of cost and mass. The accumulator, on the other hand, does not have a clear flow limit; but, like all hydraulic components, will exhibit higher flow-based energy losses at higher flow rates. Besides these general principles, no studies were found which directly compared power densities of accumulator and flywheel energy storage in hydraulic systems.

The overall trade-off between flywheels and accumulators is one of specific energy and efficiency. As noted above, hydraulic accumulators can exhibit round trip efficiencies as high as 95% (Pourmovahed *et al.* 1988) but their specific energies only approach $2.5\frac{\mathrm{Wh}}{\mathrm{kg}}$ (Alson *et al.* 2004, Steelhead Composites 2015). Flywheels, on the other hand, have specific energies of $8-14\frac{\mathrm{Wh}}{\mathrm{kg}}$ but lower round trip efficiencies, on the order of 70–80% (Hansen and O'Kain 2011), which is dominated by energy losses in the pump/motor (Shimoyama *et al.* 2010, Triet and Ahn 2011).

Some have proposed mitigating the state-of-charge-dependent pressure of the accumulator through the use of hydraulic transformers. Hydraulic transformers are mechanical devices which convert pressure and flow. For instance, a transformer might accept low-pressure hydraulic fluid at a high flow rate and discharge higher pressure hydraulic fluid at a lower flow rate. Hydraulic transformers allow a driven component to be supplied with hydraulic fluid pressure decoupled from accumulator pressure (Achten *et al*. 2008, Achten and Bv 2008, Wu *et al*. 2014). This benefit is provided at the expense of the increased complexity and energy loss incurred in the transformers.

Figure 2 presents a comparison of the relationship between stored usable energy and mass for commercial flywheels (Hansen and O'Kain 2011) and commercial gas-charged accumulators (Steelhead Composites 2015). The horizontal lines, which represent a recommended energy storage value for several hydraulic hybrid vehicles, are based on the energy recovered for the vehicle decelerating from highway speed (Hansen and O'Kain 2011). These values are for reference only since hydraulic energy storage and hybridisation have many other applications. Also included is the average of the range of specific energy predicted for the strain energy accumulator (Pedchenko and Barth 2009). This value does not included the required containment device (Tucker and Barth 2013). Also included are the predicted properties of the prototype scale Hydraulic Flywheel Accumulator, a device that includes flywheel and accumulator components and will be discussed below (Strohmaier 2014).

Flywheel hydraulic systems

As mentioned earlier, implementing a flywheel storage device in a hydraulic system requires a hydraulic pump/motor. Since the pump/motor is often the most significant source of energy loss in the flywheel storage unit, the system circuit topology and the control is non-trivial. As modern flywheels often spin much faster than the rated speed of typical hydraulic pump/motors, a gearbox or transmission is usually required. Such a storage device has been developed and implemented on an excavator by Ricardo, who also holds several patents on portions of the device (Atkins *et al.* 2016, Ricardo 2014). However, the implementation of such a device is more complex than simply replacing the accumulator because the displacement of the hydraulic pump/motor determines the flow rate but not the pressure. This can present challenges or benefits, depending on the type of driven component, and can allow more efficient control of certain types of loads (Grabbel and Ivantysynova 2005). If the load is another hydraulic pump/motor, the system is identical to a hydrostatic transmission and precise control of the displacements of one or both units will determine the speed or torque applied to the load. If both units have variable displacement, this provides a free degree of freedom, allowing the system to be operated at various pressures, depending on the load power. This degree of freedom has traditionally been used to operate the system at a constant pressure, in a configuration known as a constant pressure system (CPS).

The constant pressure system

Although the concept of using hydraulic accumulators to buffer the loads experienced by mechanical or electric powertrains is not new (Otis 1980), the CPS in the form shown above was first proposed by Kita (1995) and Nakazawa *et al*. (1996). The system involves a variable displacement hydraulic pump/motor coupled to a flywheel, sometimes through a clutch, as shown in Figure

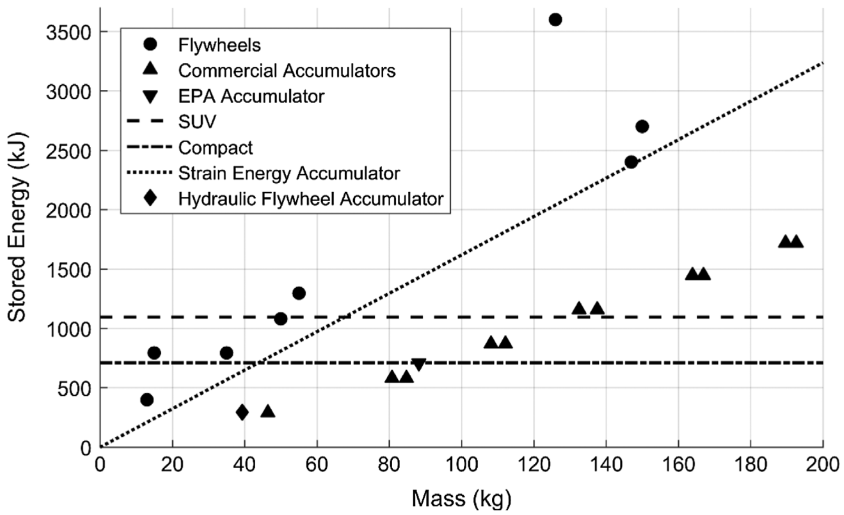

Figure 2. Approximate usable stored energy and mass for various energy storage devices, including: commercial flywheels ● (Hansen and O'Kain 2011), commercial composite accumulators ▲ (Steelhead Composites 2015), prototype accumulator used in EPA Hydraulic Hybrid vehicle study ▼ (Alson *et al*. 2004), and for reference, recommended energy storage requirements for two different vehicles --, - - - (Hansen and O'Kain 2011). Also included are a line representing the projected specific energy of the strain energy accumulator ... (Pedchenko and Barth 2009), and the proposed Accumulator prototype ◆ (Strohmaier 2014).

3. The displacement of the hydraulic pump/motor is then adjusted as necessary to keep the system pressure relatively constant. Nakazawa presented two topologies of this open loop system, both applied to a hydraulic hybrid passenger vehicle as it completed the Japanese 10 mode driving schedule. The two topologies primarily differed in the inclusion of a clutch between the flywheel and the flywheel-pump/motor and the size of their accumulators. The flywheel-pump/motor control used a pressure band strategy and involved switching between unclutched, clutched and fully motoring or clutched and fully pumping states, based on system pressure set points. The study found that the first topology, without a clutch, was more efficient than a conventional vehicle only for severe drive cycles. The second topology, with the clutch, was more efficient than the first topology and more efficient than the traditional vehicle for all drive cycles simulated. The second topology used 28–50% less prime mover energy in the 10 mode driving schedule (Nakazawa *et al.* 1996). Some of Nakazawa's results were republished by Wan *et al.* (2003). These studies showed that, at least in simulation, flywheel energy storage in hydraulic systems can be effective in energy recovery and reuse. In these studies, the more efficient topology used a larger accumulator and pressure band control. Both of these choices have the potential to improve efficiency since the accumulator is typically more efficient than the flywheel-pump/motor and the flywheel-pump/motor is, in general, more efficient when operated at higher displacements. It is not clear which of these effects is dominant. In any event, their combination resulted in a significantly more efficient system.

The CPS was also studied by Hao et al., who modelled and simulated two systems, one with a flywheel but no accumulator that operated at nearly constant pressure, and one with an accumulator but no flywheel. This team simulated both systems using the 10 mode driving schedules and compared the effect of using a dual pressure set point control strategy and/or a two-gear transmission between the engine and the hydraulic pump/motor. The pressure control strategy was implemented by controlling pressure at 15 MPa when the vehicle was stopped or at a constant velocity, and at 20 MPa when the vehicle was accelerating or decelerating. Both control strategies reduced fuel consumption in the simulation by allowing the pump/motor units to operate at higher displacements. In these simulations, the accumulator system was more efficient, but both systems performed better than the conventional vehicle (Hao *et al.* 1999).

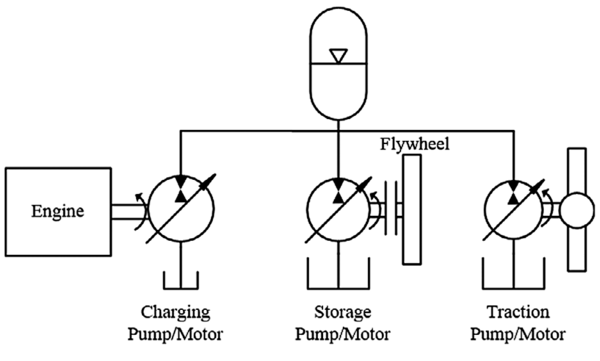

Figure 3. Example constant pressure system (CPS) (Nakazawa *et al.* 1996).

Yokota extended Nakazawa's research by conducting experiments and developing an addition control strategy. His control strategies included the proportional and pressure band methods of Nakazawa in addition to a proportional/hysteresis control. This method involved pressure set points that determined when the flywheel-pump/motor began operating proportionally, essentially a combination of the previous two control strategies. Yokota simulated this new control strategy and found it to be less efficient than the pure on/off strategy. Yokota also experimentally tested all three control strategies, although without a clutch. The lack of a clutch resulted in the experimental systems exhibiting low efficiency. However, the models suggest that the inclusion of a clutch would result in both the on/off and hysteresis control modes improving fuel consumption over the conventional vehicle (Yokota *et al.* 2002). Yokota's work was the first experimental verification of the CPS models and validated the feasibility of such a design. In simulation, the on-off strategy was more efficient, with a fuel efficiency of 26.5 km/l compared to the 11.5 km/l for the conventional vehicle, or 56.6% less prime mover energy. However, in the experiment the on-off strategy was much less efficient, at approximately 8 km/l, or 43.8% more prime mover energy. This is due to the inclusion of a clutch in the simulation but not in the experiment. The on-off strategy, without a clutch, resulted in the flywheel-pump/motor operating at zero displacement for much of the drive cycle. Significantly, the study found that a clutched, fixed displacement pump/motor to be the optimal design and control strategy for a CPS that includes an accumulator.

The simulation results of Nakazawa were further validated by Ichiryu (2010, 2005) and Shimoyama *et al.* (2010) who conducted their own experiments and simulation of a CPS system. They tested idling speed loss in the flywheel-pump/motor both with and without a clutch, providing experimental evidence for the importance of minimising flywheel loss during idling periods through the use of a clutch. Ichiryu's team then went on to simulate additional control strategies. The first control method involved a much narrower pressure band than Nakazawa had used. The second method involved a proportional strategy similar to the two-pressure method used by Hao. The final control method was a combination, controlling the system pressure in one of two pressure bands using the on/off strategy. Ichiryu's team saw good agreement between simulated and experimental values of efficiency and provided further experimental validation of the concept of a hydraulic CPS. Ichiryu's study obtained energy recovery efficiencies of 78 and 73% for simulation and experiment respectively. The third control strategy, in simulation, delivered a fuel efficiency of 23.5 km/l in a vehicle with a conventional efficiency of 8–9 km/l, or 61.7% less prime mover energy compared to the conventional vehicle. The researchers acknowledge that this control strategy cannot be implemented since it changes pump/motor displacement too rapidly (Ichiryu 2010, Shimoyama *et al.* 2010).

Neither Nakazawa, Yokota, nor Ichiryu include much detail about the effect of the accumulator on their systems. It can be deduced that Nakazawa's accumulator is storing between 47 and 60% of the energy that the flywheel is storing. Yokota's accumulator is large as well, with a volume of 10L, and stores a not insignificant amount of energy over the course of the drive cycle. Ichiryu provides neither pressure not volume for his accumulators, but states explicitly that the accumulator is for the purpose of pulsation absorption. The division of power or energy between the flywheel and accumulator in these studies is unclear.

Switching-type closed loop CPS

Ahn's research group at the University of Ulsan has published extensively on hydraulic energy recovery systems, most of it not involving flywheels (Ho and Ahn 2010, Do *et al.* 2011, Do and Ahn 2012, Ho and Ahn 2012). Ahn's team did presented data that appears to be identical to that presented by Yokota in 2004 (Oh *et al.* 2004). In publications in 2005 through 2008 they proposed the switching-type closed loop CPS (SCL-CPS), which is a closed loop version of the CPS designed so that either side of the hydraulic circuit can operate at high pressure in order to avoid sharp pressure transients experienced by CPS systems when the hydraulic pump/motors shift over centre. The system was simulated, but not in a drive cycle. Instead various braking strategies were studied, including various proportional control strategies (Ahn and Oh 2005, Cho, Ahn, J. I. Yoon, *et al.* 2007, Cho, Ahn, J. H. Yoon, *et al.* 2007), as well as constant deceleration, constant torque and parabolic vehicle velocity (Ahn *et al.* 2008). One of the studies also varied pressure, but most of the runs varied the constant pressure value of the system. The accumulator pre-charge pressures were

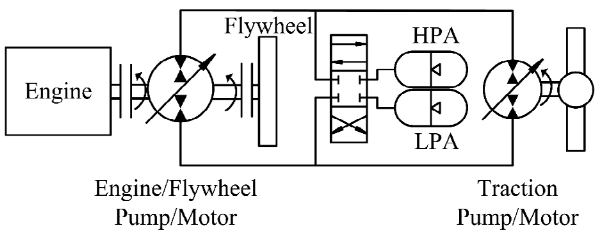

Figure 4. Hydro-mechanical hybrid storage system (Triet and Ahn 2011).

again not mentioned and it does not appear that significant energy is stored in the accumulator. This assumption is further reinforced by the fact that the high-and low-pressure sides of the system switch depending on whether the vehicle is accelerating or braking (Ahn and Oh 2005, Cho, Ahn, J. I. Yoon, *et al.* 2007, Cho, Ahn, J. H. Yoon, *et al.* 2007, Ahn *et al.* 2008).

Yang also studied a hydraulic system with a flywheel for energy storage, operated in a vehicle drivetrain (Yang 2012). However, Yang's system included no accumulator and the traction pump/motor, which provided the demand, was a fixed displacement unit. The concept, to which Yang gives the name flow-coupled flywheel vehicle, is to control the traction pump/motor torque by adjusting the differential pressure across the pump/motor. The concept is useful but Yang's circuit drawings have one side of the traction pump/motor attached directly to tank and include a check valve across the pump/motor. This would prohibit the traction pump/motor from regenerating energy or generating braking energy at all (Yang 2012).

In order to save on the number of pump/motors required, Yang's flywheel-pump/motor was shared with the engine, having separate clutches to separate the pump from the engine and flywheel. Unlike Nakazawa's and Ichiryu's studies, this requires the power source, in this case the engine, to either include a transmission or to operate at varying, and most likely non-optimal, speeds as the flywheel charges.

The most complete study to date of a hydro-mechanical hybrid storage system, a system that combines separate flywheel and accumulator energy storage, is by Triet and Ahn. Their system, which is shown in Figure 4, also involves the flywheel and engine sharing a pump/motor unit and has both an accumulator and a flywheel explicitly for energy storage. Unlike the previous systems, in this system, the flywheel clutch and the accumulator valve allow the power flow in the system to be controlled, allowing power to be transferred to or from the accumulators or the flywheel or both.

This system was simulated and compared with experiments for several simple braking and accelerating events. The system was controlled first as a traditional hydrostatic transmission (HST), then as a CPS, and finally using a new control strategy. This proposed control strategy is not described in detail, but appears to involve using the flywheel energy storage to maintain accumulator pressure within a band, very similar to that used by Nakazawa and Ichiryu. The simulations found the system could recover 78% of braking energy and the experiments showed the system used 48% less prime mover energy compared to the HST. The proposed control strategy required the least energy from the engine (Triet and Ahn 2011).

Guo *et al.* (2014) presented a hydraulic system functionally identical to that proposed by Triet and Ahn

(2011), but they instead proposed to employ a kinetic energy recovery system in an otherwise entirely electric vehicle. Guo's team experimented with various hydraulic accumulator (4, 6.3 and 10 L) and pump/motor (4, 5, 6, 8 and 10 cc/rev) sizes. It does not appear that the torque or speed of the flywheel, which functioned as the load, were controlled since the pump displacement was constant during each test. The tests validated the time-averaged behaviour of a combination of components which have previously been individually subjected to more rigorous experimental validation (McCandlish and Dorey 1984, Pourmovahed *et al.* 1988, 1992b, Hong and Doh 2004, Wang 2012).

Hydraulic flywheel accumulator

Another method of combining kinetic and pneumatic potential energy storage in one system is the Hydraulic Flywheel Accumulator proposed by Van de Ven (2009). The device spins a piston-style accumulator about its axis, thereby storing energy in the accumulator's pressurised gas as well as the kinetically in the rotating fluid and structural components of the accumulator. The purpose of this device, besides storing more energy than a traditional accumulator of the same dimensions, is to make use of the pressure dynamics of a rotation fluid (Strohmaier and Van de Ven 2013). This dynamic was further explored by Wang *et al.* (2015). The study of this device found it to provide higher specific energy than a traditional accumulator, while being more efficient than a flywheel storage system. The studies also found the benefits of fluid angular velocity to be minor while requiring more complexity and energy loss than a separate flywheel and accumulator. The added complexity is due to the high speed rotary union and the effect of angular velocity on the piston seals. The added energy losses are due to the rotary union and the acceleration of the rotating fluid (Strohmaier and Van de Ven 2013, Strohmaier *et al.* 2014, Strohmaier 2014, Strohmaier *et al.* 2015).

Summary and conclusion

This paper has examined the state-of-the art in mechanical energy storage devices for hydraulic systems. Although accumulators are widely used in hydraulic systems, recent studies have presented new ways of increasing the efficiency and specific energy. Flywheels are also by no means new but improvements in composite materials, continuously variable transmissions, and magnetic bearings have made them viable alternatives for many energy storage applications. However, their application to hydraulic systems is still in its infancy. In spite of the promising studies examined here only two commercial prototypes, an excavator by Ricardo (2014) and a bus built by Maschinenfabrik Augsburg-Nürnberg (M.A.N.) (Martini 1984, Beachley and Frank 1980), have seen their use as energy storage in hydraulic regeneration systems. The potential of utilising two energy storage devices, which has provided significant benefit in electrical energy regeneration systems (Cao *et al.* 2012), has not been fully explored in the context of hydraulic power recovery. Several control strategies have been proposed, simulated, and tested experimentally. These strategies have been tested and simulated but only in the 10 mode and modified 10 mode drive cycle, which, for most of the tests, were too short to require flywheel charging using the engine.

Specific research questions remain regarding the design and control strategies of combined flywheel and accumulator energy storage systems. The control strategies employed have been simple, which is perhaps to be expected for preliminary studies. How varying the pressure in a CPS, beyond the two set points used by Ichiryu (Shimoyama *et al.* 2010), could affect the performance of the system in various applications in still unknown. The studies have either used relatively constant pressure, storing little energy in the accumulator, or have used the flywheel to charge the accumulator between set points. The design of the hydro-mechanical hybrid storage system allows for the possibility of more complex control strategies and power sharing between the kinetic and potential energy storage devices. The system has the potential to switch between CPS mode and a pressure band control mode, as well as vary the pressure band. Whether a more complex control strategy would be beneficial, and how it should depend on application and drive cycle is still unexplored.

Also unanswered is how the accumulator should be sized relative to the flywheel size for various applications. The question of energy storage size is nontrivial even for systems with only one storage device (Pourmovahed 1993). While Strohmaier's optimisation explored trade-offs between the ratios of kinetic and pneumatic energy storage in one application (Strohmaier *et al.* 2015), that dynamic has not been examined in the context of the hydro-mechanical hybrid storage system or in applications where the load is not a hydraulic pump/motor unit propelling a vehicle. The question of which systems or topologies provide optimal specific power remains unanswered as well.

If the outstanding questions regarding the control and design of such systems were addressed, the hydro-mechanical hybrid storage system could provide significant improvement to the efficiencies achievable by mobile hydraulic systems.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Center for Compact and Efficient Fluid Power through a grant from the National Science Foundation [grant number 0540834].

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References

Achten, P.A.J. and Bv, I., 2008. A serial hydraulic hybrid drive train for off-road vehicles. *In*: *Proceedings of the national conference on fluid power*. Milwaukee, WI, 515–521.

Achten, P., *et al.*, 2008. Design and fuel economy of a series hydraulic hybrid vehicle. *Proceedings of the JFPS international symposium on fluid power*, 2008 (7–1), 47–52.

Ahn, K.K. and Oh, B.S., 2005. An experimental investigation of energy saving hydraulic control system using switching type closed loop CPS. *In: Proceedings of the Sixth Internationa l Conference on Fluid Power Transmission and Control (ICFP 2005)*, Huangzhou. IEEE Press.

Ahn, K.K., Ho, T.H., and Dinh, Q.T. 2008. A study on energy saving potential of hydraulic control system using switching type closed loop constant pressure system. *In:* Proceedings of the 7th JFPS International Symposium on Fluid Power, Toyama, 317–322.

Alson, J., *et al.* 2004. Progress report on clean and efficient automotive technologies under development at EPA. *United States Environmental Protection Agency, EPA420*.

Altair. 2011. Altair productdesign unveils the world's first series hydraulic hybrid transit bus. *Altair*. Available from: http://www.altairproductdesign.com/newsdetail.aspx?news_id=10588&news_country=en-US [Accessed 24 January 2016].

Atkins, A.F., *et al.*, 2016. *A magnetic gear*. US Patent Application US9704631 B2.

Bakholdin, D., Bosley, R.W., and Rosen, H.A. 1996. Flywheel Rotor with Conical Hub and Methods of Manufacture Therefor. U.S. Patent 5,566,588, (1), 1–5.

Barth EJ *et al.*, 2014. *High energy density elastic accumulator and method of use thereof*. U.S. Patent 8,826,940.

Beachley, N.H. and Frank, A.A., 1980. Control considerations for a flywheel hybrid automobile with a mechanical continuously-variable transmission. *In: Flywheel Technology Symposium*. Arizona: Scottsdate, 188–198.

Bleuler, H., *et al.*, 2009. *Magnetic bearings: theory, design, and application to rotating machinery*. Springer Science & Business Media.

Cao, J., Emadi, A. and Member, S., 2012. A new battery/ultracapacitor hybrid energy storage system for electric, hybrid, and plug-in hybrid electric vehicles. *In: Power Electronics, IEEE Transactions on*. 122–132.

Caterpillar, 2013. 336E H Hydraulic Excavator. *Caterpillar product brochure*. Available from: http://s7d2.scene7.com/is/content/Caterpillar/C811713 [Accessed 20 October 2015].

Cho, Y.R., Ahn, K.K., Yoon, J.I., *et al.*, 2007. A study on the energy saving hydraulic system using constant pressure system. *KFPS*, 4 (1), 7–12.

Cho, Y.R., Ahn, K.K., Yoon, J.H., *et al.*, 2007. An experimental study on the energy saving hydraulic control system using constant pressure system. *Journal of the Korean Society for Precision Engineering*, 24 (5), 68–76.

Cummins, J.J. *et al.*, 2014. Advanced strain energy accumulator: materials, modeling and manufactur. *In: Proceedings of the ASME/BATH 2014 Symposium on Fluid Power & Motion Control*. Bath, UK, 1–8.

Do, H.T. and Ahn, K.K., 2012. A study of energy saving hydraulic system by a pressure coupling hydrostatic transmission. *Transactions of the Society of Mechanical Engineers (유공압건설기계학회논문집)*, 9 (1), 10–17.

Do, H.T. *et al.*, 2011. Development of a novel hydrostatic transmission system for braking energy regeneration. *In: Proceedings of the 8th JFPS International Symposium on Fluid Power*. Okinawa, 85–91.

Genta, G., 1985. *Kinetic energy storage: theory and practice of advanced flywheel systems*. London: Butterworth & Co.

GMN, 2014. High Precision Ball Bearings. *GMN High Precision Ball Bearings Catalog*. Available from: http://www.gmnbt.com/pdf/catalog-BallBearings.pdf.

Grabbel, J. and Ivantysynova, M., 2005. An investigation of swash plate control concepts for displacement controlled actuators. *International journal of fluid power*, 6 (2), 19–36.

Guo, Y., Ning, X., and Wei, D., 2014. Analysis on energy recovery efficiency of hydraulic regenerative braking system. 机电工程, 31 (6), 721–724.

Ha, S.K., Kim, D.J. and Sung, T.H., 2001. Optimum design of multi-ring composite flywheel rotor using a modified generalized plane strain assumption. *International journal of mechanical sciences*, 43, 993–1007.

Ha, S.K., *et al.*, 2006. Design and spin test of a hybrid composite flywheel rotor with a split type hub. *Journal of composite materials*, 40 (23), 2113–2130.

Ha, S.K., Han, H.H. and Han, Y.H., 2008. Design and manufacture of a composite flywheel press-fit multi-rim rotor. *Journal of reinforced plastics and composites*, 27 (9), 953–965.

Ha, S.K., Kim, J.H. and Han, Y.H., 2008. Design of a hybrid composite flywheel multi-rim rotor system using geometric scaling factors. *Journal of composite materials*, 42 (8), 771–785.

Hansen, J. and O'Kain, D.U., 2011. *An assessment of flywheel high power energy storage technology for hybrid vehicles*. Oak Ridge, TN: SciTech Connect.

Hao, J., *et al*., 1999. Energy-saving of a hybrid vehicle using a constant pressure system. *JFPS*, 30 (1), 20–27.

Hayat, K., *et al*., 2006. Design, fabrication and testing of a hybrid composite flywheel rotor & hub. *International conference on composite materials*, 1–6.

Ho, T.H. and Ahn, K.K., 2010. Modeling and simulation of hydrostatic transmission system with energy regeneration using hydraulic accumulator. *Journal of mechanical science and technology*, 24 (5), 1163–1175.

Ho, T.H. and Ahn, K.K., 2012. Design and control of a closed-loop hydraulic energy-regenerative system. *Automation in construction*, 22, 444–458.

Hong, Y.-S. and Doh, Y.-H., 2004. Analysis on the friction losses of a bent-axis type hydraulic piston pump. *KSME international journal*, 18 (9), 861–8611679.

Ichiryu, K., 2005. Experimental investigation of a hybrid vehicle. *Proceedings of the JFPS international symposium on fluid power*, 2005 (6), 232–238.

Ichiryu, K., 2010. Hybrid vehicle using constant pressure hydraulic system with flywheel for energy storage. *Journal of drive and control*, 7 (2), 33–41.

Janse Van Rensburg, P.J., Groenwold, A.A, and Wood, D.W., 2013. Optimization of cylindrical composite flywheel rotors for energy storage. *Structural and multidisciplinary optimization*, 47, 135–147.

Jian, L., *et al*., 2009. Comparison of coaxial magnetic gears with different topologies. *IEEE transactions on magnetics*, 45 (10), 4526–4529.

Kim, S.J., *et al*., 2014. Design and fabrication of hybrid composite hubs for a multi-rim flywheel energy storage system. *Composite structures*, 107, 19–29.

Kita, Y., 1995. Recommendation of constant pressure system. *Journal of the Japan hydraulics and pneumatics*, 25 (1), 46–53.

Li, P.Y., Van de Ven, J.D. and Sancken, C., 2007. Open accumulator concept for compact fluid power energy storage. *Proceedings of IMECE*, 127–140.

Li, P.Y. *et al*., 2011. Compressed Air Energy Storage for Offshore Wind Turbines. *In: National Conference on Fluid Power, International Fluid Power Exposition*. Las Vegas.

Love, L.J., Lanke, E. and Alles, P., 2012. *Estimating the impact (Energy, emissions and economics) of the U.S. fluid power industry*. Oak Ridge, TN: Oak Ridge National Laboratory (ORNL).

Mallick, K., 2015. The lighter side of accumulators. *Hydraulics & pneumatics*, 1–5. Available from: http://hydraulicspneumatics.com/accumulators/lighter-side-accumulators [Accessed 5 May 2016].

Martini, S., 1984. The M.A.N. hydrobus: A drive concept with hydrostatic brake energy recovery. *In: International symposium on advanced and hybrid vehicles*. University of Strathclyde, 227–234.

McCandlish, D. and Dorey, R.E., 1984. The mathematical modelling of hydrostatic pumps and motors. *Proceedings of the institution of mechanical engineers, part B: Management and engineering manufacture*, 198 (3), 165–174.

Nakazawa, H., *et al*., 1996. A hydraulic constant pressure drive for engine-flywheel hybrid vehicles. *Proceedings of the JFPS international symposium on fluid power*, 513–518.

Oh, B.-S., Ahn, K.-K. and Cho, Y., 2004. A study on the hydraulic pump/motor control in the flywheel hybrid vehicle. *ICCAS*, 2004, 307–311.

Otis, D.R., 1980. Hydraulic accumulators as energy buffers. *In: Flywheel Technology Symposium*. Scottsdate, Arizona, 404–413.

Parker Hannafin, 2016. Lightraulics composite hydraulic cylinders. *Parker Catalog*. Available from: https://www.parker.com/literature/Cylinder Europe/Cylinder Europe - English Literature/Composites/Composite Cylinders_1410-UK.pdf [Accessed 5 May 2016].

Pedchenko, A. and Barth, E.J., 2009. Design and validation of a high energy density elastic accumulator using polyurethane. *ASME 2009 dynamic systems and control conference*, Hollywood, California, Vol. 1, i, 283–290.

Pourmovahed, A., 1988. Energy storage capacity of gas-charged hydraulic accumulators. *In: Thermophysics, plasmadynamics and lasers conference*. San Antonio, TX, 4–7.

Pourmovahed, A., 1990. Durability testing of an elastomeric foam for use in hydraulic accumulators. *Journal of solar energy engineering*, 112, 223–228, August.

Pourmovahed, A., 1993. Sizing energy storage units for hydraulic hybrid vehicle applications. *ASME, dynamic systems and control: advanced automotive technologies*, 52, 231–246.

Pourmovahed, A. and Otis, D.R., 1990. An experimental thermal time-constant correlation for hydraulic accumulators. *Journal of dynamic systems, measurement, and control*, 112 (1), 116.

Pourmovahed, a., *et al*., 1988. experimental evaluation of hydraulic accumulator efficiency with and without elastomeric foam. *Journal of propulsion*, 4 (2), 185–192.

Pourmovahed, A., Beachley, N.H. and Fronczak, F.J., 1992a. Modeling of a hydraulic energy regeneration system: Part I—analytical treatment. *Journal of dynamic systems, measurement, and control*, 114 (1), 160.

Pourmovahed, A., Beachley, N.H. and Fronczak, F.J., 1992b. Modeling of a Hydraulic Energy Regeneration System: Part II—Experimental Program. *Journal of dynamic systems, measurement, and control*, 114 (1), 160–165.

Ricardo, 2014. Ricardo to showcase "TorqStor" high efficiency flywheel energy storage at CONEXPO. Available from: http://www.ricardo.com/en-GB/News–Media/Press-releases/News-releases1/2014/Ricardo-to-showcase-TorqStor-high-efficiency-flywheel-energy-storage-at-CONEXPO/ [Accessed 9 March 2015].

Saadat, M. and Li, P., 2015. Combined Optimal Design and Control of a Near-isothermal Liquid Piston Air Compressor/Expander for a Compressed Air Energy Storage (CAES) System for Wind Turbines. In *Proc. 2015 ASME-DSCC*, Columbus, OH.

Shimoyama, H., *et al*., 2010. *Study on hybrid vehicle using constant pressure hydraulic system with flywheel for energy storage*. SAE Technical Paper Series. No. 2004-01-3064.

Spears, W. *et al*., 2010. *Composite hub for high energydensity flywheel*. U.S. Patent Application 12/181,012, filed 28 July.

Steelhead Composites, 2015. Bottom repairable lightweight high pressure composite accumulator. *Catalog*. Available from: http://steelheadcomposites.com/shc/wp-content/plugins/pdf-viewer-for-wordpress/web/viewer.php?file=http://steelheadcomposites.com/shc/wp-content/uploads/2015/05/SHC-BR6000.pdf [Accessed 15 January 2016].

Stoneburner, B.M. and Technologies, A.I., 2005. Hybrid ceramic bearings : more mettle than metal. *Plant Engineering*, 59 (8), 71–73.

Strasik, M., *et al.*, 2007. Design, fabrication, and test of a 5-kWh/100-kW flywheel energy storage utilizing a high-temperature superconducting bearing. *IEEE transactions on applied superconductivity*, 17 (2), 2133–2137.

Strasik, M., *et al.*, 2010. An overview of Boeing flywheel energy storage systems with high-temperature superconducting bearings. *Superconductor science and technology*, 23 (3), 034021.

Strohmaier, K.G., 2014. *Modeling, optimization, and detailed design of a hydraulic flywheel-accumulator*. Thesis. University of Minnesota.

Strohmaier, K.G. and Van de Ven, J.D., 2013. Constrained multi-objective optimization of a hydraulic flywheel accumulator. *In*: *Proceedings of the ASME/BATH 2013 symposium on fluid power & motion control*, Sarasota, FL, USA.

Strohmaier, K.G., *et al.*, 2014. "Experimental studies of viscous loss in a hydraulic flywheel accumulator." *In*: *National conference on fluid power, international fluid power exposition*. Las Vegas, NV, 0369-000017.

Strohmaier, K.G., Cronk, P.M., and Van de Ven, J.D., 2015. Design optimization of a hydraulic flywheel accumulator for a hydraulic hybrid vehicle. *International journal of fluid power*, 1–13.

Triet, H.H. and Ahn, K.K., 2011. Comparison and assessment of a hydraulic energy-saving system for hydrostatic drives. *Proceedings of the institution of mechanical engineers, Part I: Journal of systems and control engineering*, 225 (1), 21–34.

Tucker, J.M. and Barth, E.J., 2013. Design, fabrication, and evaluation of a distributed piston strain-energy accumulator. *International journal of fluid power*, 14 (1), 47–56.

Van de Ven, J., 2009. Increasing hydraulic energy storage capacity: flywheel-accumulator. *International journal of fluid power*, 10 (3), 41–50.

Van de Ven, J.D., 2013. Constant pressure hydraulic energy storage through a variable area piston hydraulic accumulator. *Applied energy*, 105, 262–270.

Volvo Car UK, 2014. Volvo Car Group and Flybrid Conduct UK Testing of Flywheel KERS Technology. *Press Release*. Available from: https://www.media.volvocars.com/uk/en-gb/media/pressreleases/141626/volvo-car-group-and-flybrid-conduct-uk-testing-of-flywheel-kers-technology [Accessed 20 October 2015].

Wan, L., Ke, J., and Xu, M., 2003. Study on the recovery of energy during automotive brake. 机床与液压, 3, 224–227.

Wang, S., 2012. Improving the volumetric efficiency of the axial piston pump. *Journal of mechanical design*, 134 (11), 111001.

Wang, C., *et al.*, 2015. "Pressure control of rotary accumulator." In: *2015, International conference on fluid power and mechatronics (FPM). IEEE*, 1395–1398.

Wu, W., *et al.*, 2014. Investigation of energy efficient hydraulic hybrid propulsion system for automobiles. *Energy*, 73, 497–505.

Yan, B., *et al.*, 2015. Experimental study of heat transfer enhancement in a liquid piston compressor/expander using porous media inserts. *Applied energy*, 154, 40–50.

Yang, X., 2012. Energy recovery efficiency of flow-coupled flywheel vehicle. *Research journal of applied sciences, engineering and technology*, 4 (17), 2905–2910.

Yokota, S., *et al.*, 2002. A flywheel hybrid vehicle making use of constant pressure system (fabrication of stationary test facility and experiment of urban driving schedule). *Transactions of the Japan society of mechanical engineers C*, 68 (671), 2127–2132.