DIGITAL DISPLACEMENT® HYDRAULIC HYBRIDS

PARALLEL HYBRID DRIVES for COMMERCIAL VEHICLES

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1. INTRODUCTION

The discussion about hybrids generally centres on the addition of electric motors and batteries to the drivelines of otherwise conventional vehicles. Passenger cars of this description have been commonplace for more than a decade, so this stance is quite understandable. However the transmission of power and storage of energy can be done using other media. Rather than electric machines, hydraulic ones can be used to transmit power. Instead of batteries or ultra-capacitors, flywheels or gas accumulators can store on-board energy. While the electric solutions have been mainstream, the hydraulic ones have been quietly emerging on larger, more specialist, vehicles. In the past two years Parker, Bosch Rexroth and Eaton have been trialling systems with vehicle integrators. In particular they have targeted refuse trucks and delivery vans.

Most current electric hybrid vehicles use a parallel architecture – where the bulk of the energy follows a mechanical transmission path through the driveline and only a small part flows through the electrical portion. This approach has been largely dictated by the power densities of electrical machines, which are considerably lower than those of mechanical gearboxes. An unavoidable drawback to parallel architecture is the addition of mass and complexity because the vehicle effectively has two transmissions. Series architecture, as practised in the BAe HybriDrive® system and the Parker Runwise® hydraulic drive, amongst others, is altogether different in that all of the power is transmitted through a non-mechanical link - over at least some of the speed range.

Artemis Intelligent Power has previously built a series hybrid vehicle based on a relatively new hydraulic pump/motor technology called Digital Displacement®. The company is convinced of the validity of both series and parallel approaches when applied appropriately according to distinct contexts. In this paper the focus is on aspects of parallel hybrid drives, which we attempt to place in relation to contemporary electrical drive systems. Rydberg (1) gives an excellent general treatment of hydraulic hybrids and shares the Artemis view that these have great potential, particularly in the commercial vehicle sector.

2. HYBRID DRIVE REQUIREMENTS

2.1. Engine size

It is tempting to think that hybridisation will offer the chance to greatly downsize the engines of conventional vehicles. In fact most commercial vehicles have a continuous peak power demand that is determined by the combination of aerodynamics, rolling resistance, grade and load rather than being influenced by acceleration times. If hybrids do not offer the chance to use smaller engines, they do give us an opportunity to run them at more efficient operating points. When one looks at an engine operating map, it is immediately obvious that the most fuel efficient operating speed is generally the lowest possible one at which adequate torque can be produced to meet vehicle power requirements. Whilst it might be good in theory to operate the engine in this way, at least during steady-state operation, it leaves the engine no headroom with which to either supply additional torque to the wheels or to speed up the crankshaft. Consequently this "best operating point" strategy effectively becomes undriveable in the real world. What is needed, to make the strategy acceptable, is some secondary power source to allow the engine to speed up and thus produce more power when the driver is demanding higher acceleration or climbing a hill. The amount of energy needed to speed up the engine is relatively small, but it must be delivered rapidly in order to provide the throttle response that drivers expect.

2.2. Recovery of braking energy

The second thing that a hybrid transmission can do is to capture braking energy and to subsequently recycle it in some economically or environmentally useful way. The power rating of the energy capture device needs to be sufficient to capture a significant amount of a typical braking event. Our analyses have shown that a useful capacity, from studying a typical drive cycle such as US FTP72, equates to the kinetic energy of the vehicle when braked from 50 km/hr. It is arguable that there is relatively little to be gained in carrying additional energy storage capacity – particularly if it is heavy or costly.

Conventional wisdom would suggest using this recovered braking energy during a subsequent acceleration – essentially using the regeneration system in reverse. But another use would be to employ the saved energy to provide on-board power during times when the vehicle is stopped - such that the engine can either be de-fuelled or turned off for a time.

The intrinsic nature of a hydraulic system seems to perfectly match the high cyclic power requirements of hybrid drives. Gas accumulators, the default storage devices for high-pressure oil systems, have relatively low energy densities - but this is of less importance given the relatively limited amount of energy that has to be stored.

So far so good, but the real problem - one that has reduced the penetration of hydraulics into many markets including hybrid - is that conventional hydraulic machines suffer from poor round trip efficiencies. The problem is particularly acute in applications, like those being considered here, where power is mostly transferred under part-load conditions in which the inherent standing losses of conventional hydraulics become significant.

3. REDUCING HYDRAULIC LOSSES

3.1. Digital Displacement® machines

The problem of low part-load efficiencies in hydraulic machines has been systematically addressed through the development of Artemis Digital Displacement® (often abbreviated to 'DD') piston pumps and pump/motors which use electronically controlled valves to manage displacement rather than mechanically commutated ports and variable piston strokes.

A Digital Displacement® machine is typically of the radial piston configuration, with the loaded bearings at the centre, where the surface velocity is lowest, and the valves around the periphery where there is more space to reduce breathing losses. This configuration by itself accounts for several efficiency points of improvement, at full output, over axial pumps and motors. The use of electronically-controlled check valves has another efficiency benefit, the valves themselves cannot open against pressure, which means that they automatically recapture the compression energy in the working fluid that is normally lost with mechanical commutation. At higher pressures this represents a further one to two percent efficiency improvement.

3.1. Selective idling

It is the mechanism of off-loading unused capacity where Digital Displacement® really differentiates itself. Conventional axial machines still carry most of their losses whilst being destroked to reduce capacity. The bearings are still loaded, compressed fluid is still being vented and high pressure fluid is still leaking at roughly the same rate. But at the same time the power throughput is being reduced, which is why efficiency suffers so badly. Digital Displacement® machines can idle unused cylinders on a stroke-by-stroke basis when they are not needed. An idle cylinder is not pressurised and therefore creates insignificant leakage and bearing load losses. Measurements show that an idle cylinder typically has a parasitic power loss of approximately one percent of its full pumping power.

By composing the output of the pump through the selection of active and idle cylinders in a smooth sequence, very close load following can be achieved with a power transmission system that has unprecedented levels of efficiency. This kind of direct digital control also resolves a long-standing problem with conventional hydraulics – it eliminates complex and lossy servo-systems which are encumbered with hysteresis and non-linearity effects. It also provides high-bandwidth response, typically on the order of 10 to 20 ms.

3.2. Losses and efficiencies

Some loss and efficiency curves from an automotive scale Digital Displacement® pump (with nominal corner power of 175 kW) are shown in Figs.1 to 3 along with comparative curves from bent-axis and swash-plate machines of similar sizes. So that the losses in kilowatts could be directly compared, the bent-axis and swash-plate data were slightly rescaled to represent machines having identical volumetric capacities to the Digital Displacement® one. The curves have been replotted from lab tests made by Sauer-Danfoss (2). The Digital Displacement® curves are in close agreement with results from similar test programmes made by three other large independent OEM companies.
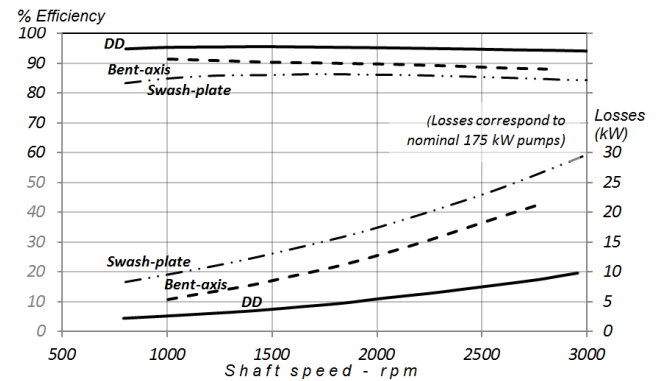

Fig.1 Losses and efficiencies against shaft speed, of hydraulic pumps operating at 100% displacement. See text for details of Figs. 1,2 & 3 which are replotted from (2).
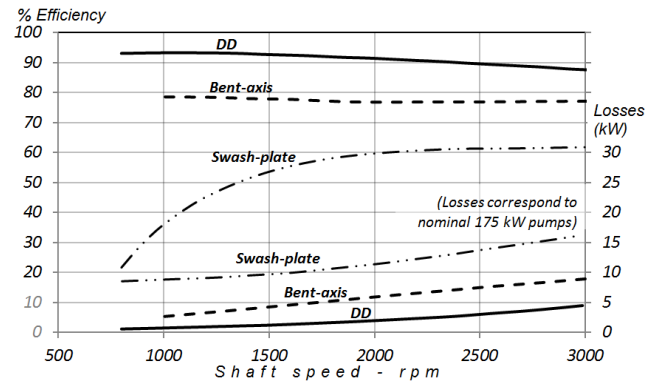

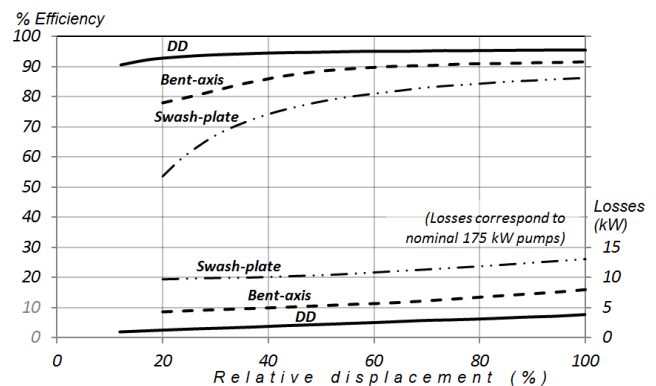Fig.2 As Figure 1, but with pumps at 20% displacement.

Fig.3 Losses and efficiencies at 1500 rpm
- against displacement.

In Figs 1, 2 & 3, pump performances are described in terms of losses in kilowatts and in terms of efficiency of conversion from shaft to fluid power. In Figure 1 and 2 these are plotted against shaft speed respectively for full displacement and for 20% displacement. In Figure 3, losses and efficiencies are plotted against displacement for a constant shaft speed of 1500 rpm. The performance of the Digital Displacement® pump is notable at all load levels with a near plateau from twenty percent displacement upwards.

3.3. Digital Displacement® Pump Motor

A motor can be created by altering the Digital Displacement® pump slightly. The passive check valves between the cylinders and the high-pressure gallery are replaced with solenoid actuated versions. By coordinating the timing of the high and low pressure valves, each cylinder can be controlled to have the high-pressure valve open on the down stroke, such that the piston acts to turn the crankshaft. The motor has a very similar efficiency map to the pump, though its apparent capacity will be reduced by about 8% due to the sequencing of the valves. A pump/motor developed by Artemis for commercial vehicle use is shown in Fig. 4. It has a geometric displacement of 480 cc/rev, a service pressure of 350 Bar, and a maximum shaft speed of 2,200 RPM.
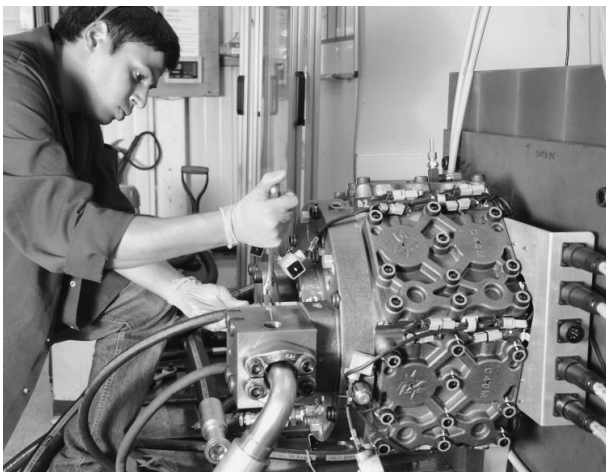

Fig.4   480 cc/rev DDPM (Digital Displacement® Pump Motor)

3.4. Gas accumulators

The obvious energy storage device for a vehicle is a gas accumulator. Their properties have been described elsewhere (3) and so it is only necessary to provide a very short summary. In vehicle use the accumulator tends to be charged and discharged in a relatively short cycle time so that thermal losses are kept relatively slight. Measurements on Artemis vehicles suggest that the efficiency of a standard bladder accumulator in such a service averages 94%. To store the optimal amount of energy needed by a single decker bus requires an accumulator with a shell volume of approximately 100 litres. The fluid, which must be pumped into the high-pressure side whilst energy is being stored, must be held at boost pressure (typically around 5 bar) on the low pressure side of the pump/motor in a second accumulator. It can be somewhat lighter due to its very limited pressure rating.

The Artemis parallel system, as proposed for frequently stopping vehicles such as city buses and refuse trucks, is essentially a bolt-on retrofittable system which couples into the final drive of the vehicle. It requires packaging space for the pump/motor and the two gas accumulators, both high and low-pressure. Figure 5 shows a typical layout on a city bus chassis. In this case the conventional driveline and the parallel driveline converge at the tandem axle but clearly many other arrangements are possible. As can be observed, the added hydraulic circuit is very simple. The pump/motor defaults to an idle condition and so, in the event of any difficulty with the regenerative system, it can be shut off with minimal impact on continuing vehicle operation.

Although not shown, the hydraulic energy stored in the accumulator can be used to power a smaller Digital Displacement® hydraulic motor driving the engine accessories. This allows them to be driven whilst the engine is off.
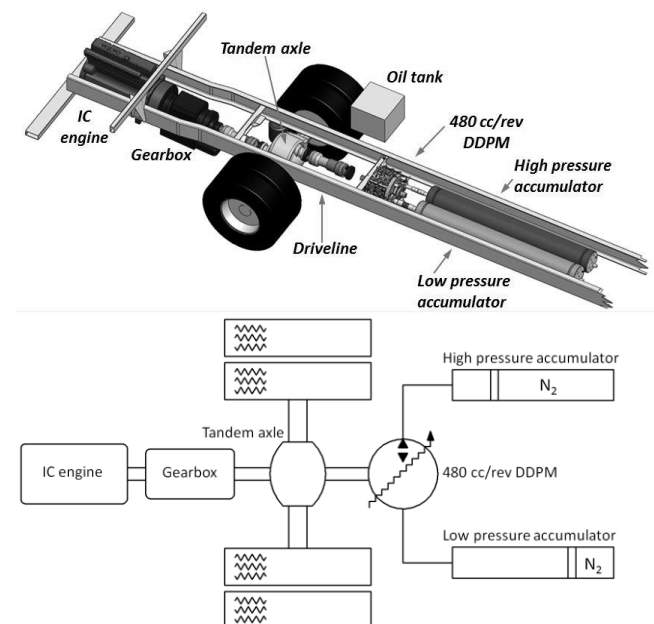

Fig.5 Simplified layout of a parallel hydraulic braking energy recovery system.

4. TEST RESULTS

4.1. City bus tests

A Volvo B7RLE single-deck city bus owned by local operator Lothian Buses was instrumented in 2009 to collect CAN data from the engine and gearbox as well as GPS position and vehicle velocity. Because GPS altitude data is not sufficiently precise, the corresponding altitudes along the route were found using the Ordinance Survey 50m altitude data set. The bus rolling resistance and aerodynamic coefficients were established experimentally from a coast-down of the bus. Data was collected along three different routes over several days.

The hybrid driveline was tested in an instrumented dynamometer cell with the pump/motor following the previously recorded velocity trace from the in-service bus. The measured fuel consumption rate from the bus was then compared with that

achieved on the dynamometer with the regeneration system enabled. The fuel saving was estimated through interpolation of an engine BSFC (brake specific fuel consumption) map. The graph in Figure 6, part of a simulation of local bus route 29, shows the velocity trace during a 20-minute period of the test along with the accumulated fuel use, both with and without regeneration.

For the typical case shown, the simulation shows that the fuel used for the entire route journey would have been reduced by 22.5% if a retrofitted parallel Digital Displacement® hybrid system had been in use. If the slightly more complex architecture with engine accessory drive had been employed, which would permit the engine to be used stop-start, there would have been a significant further uplift in fuel saving.
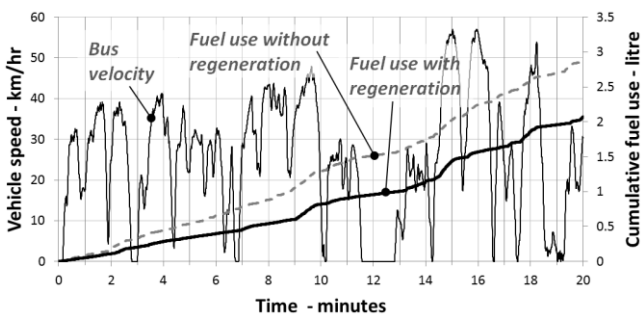

Fig.6 Simulated fuel use by bus with and without hybrid braking energy regeneration system – an example 20 minute section of Lothian Buses Route 29.

Artemis has also made a series hybrid Digital Displacement® transmission, tested in a BMW 530, which achieved a 50% reduction in urban fuel use in third party tests conducted in the Millbrook laboratory. As a result we are very confident that the modelling and simulation techniques used on the bus hybrid are both appropriate and accurate.

5. COMPARISON TO ELECTRICAL PARALLEL HYBRID SYSTEMS

It will be helpful to compare a Digital Displacement® parallel system with its already established rivals. While there are many different characteristics to compare, perhaps we should start with the basics of weight, cost, efficiency and pay-back time. Whilst we are very confident of the numbers we use for a Digital Displacement® parallel system, we are relying on third party information with regards to the specifications of electric hybrid components.

The Digital Displacement® parallel system with the architecture shown in Fig. 5 is compared to two electrical hybrid systems. Tables 1, 2 & 3 compare cost, weight and throughput efficiency of each component along the driveline. Costs are based on expected component lifetimes during the service life of the vehicle. The assumptions used in arriving at the estimated costs are shown at the bottom of Table 1.

According to the figures in these tables it is apparent that the Digital Displacement® system has a significantly higher efficiency, lower capital cost, is a third of the weight of a battery-

electric system, requires less expensive upkeep and, most importantly, has a much shorter pay-back time.

Of course there are other metrics which might be compared, for example the safety of battery and high-voltage systems versus that of a composite pressure vessel – particularly in the event of an accident. Cold performance, recyclability of the constituent materials and the requirement of strategic metals are other aspects that might also affect the success of one type of system relative to the others. Digital Displacement® has advantages in each of these areas.

Table 1   Comparison of hybrids – cost

	Primary machine UK£k	System controller UK£k	Energy store UK£k	Bal.of system UK£k	**Install cost UK£k**	15-year O&M UK£k	**15-year cost UK£k**
Battery electric	2 [1]	2 [2]	6 [3]	1 [4]	**11**	8 [5]	**19**
Supercap electric	2 [1]	4 [6]	10 [7]	1 [4]	**17**	12 [8]	**29**
Hydraulic DDPM	1.6 [9]	0.4 [9]	2.25 [10]	1.5 [4]	**5.3**	3 [11]	**8.2**

Notes to superscripted numbers
[1] Estimated from published weights & known materials.
[2] Based on prices from volume supplier.
[3] Based on £44/kW and peak power. Includes battery management system.
[4] Balance of system. Estimated ball-park figure.
[5] Battery pack replaced every 5 years.
[6] Estimated upscale from (2) based on higher V and I ratings.
[7] From volume supplier. Includes more complex management system.
[8] Supercapacitor replaced once.
[9] From known Artemis machines with allowance for volume manufacture.
[10] Based on known costs of 37 litre, carbon-fibre accumulators.
[11] Replace accumulators once, HP hoses twice, & oil five times.

Table 2   Comparison of hybrids – efficiency

	Primary machine %	System controller %	Energy store %	Bal.of system %	**System efficiency %**
Battery electric	92	90	87	98	**59**
Supercap electric	92	85	90	98	**54**
Hydraulic DDPM	95	100	94	98	**83**

Table 3   Comparison of hybrids - weight

	Primary machine	System controller	Energy store	Bal.of system	**Total weight**
Battery electric	110	100	770	100	**1080**
Supercap electric	110	100	200	150	**560**
Hydraulic DDPM	200	2	35	100	**340**

6. FUTURE PLANS

Artemis is building two regenerative vehicle systems for test in the current year. One is a high torque variant of the system described in this paper, the other a smaller retrofittable system which can capture braking energy to drive the engine accessory load and significantly reduce fuel use. It plans to demonstrate these to partners and customers in 2014.

7. SUMMARY

Artemis has developed a parallel Digital Displacement® hydraulic hybrid system which has been prototyped at commercial vehicle scale. It has been tested in a dynamometer cell using velocity and load data gathered from an actual Lothian Bus single-decker on its daily route. Throughput efficiencies of regeneration energy and accumulated fuel savings have been measured.

The Digital Displacement® system has been benchmarked against existing electric parallel hybrid systems to establish its competitiveness in this very significant market space.

The hydraulic system has a significantly higher throughput efficiency than conventional electric systems, due to the high efficiency of the hydraulic machines and the low losses of the energy storage accumulator.

The weight of the hydraulic system is also significantly less than its electric rivals, particularly due to the high power density of the accumulators and the fact that all of their stored energy can be cycled without negative consequences.

Initial system cost of the hydraulic system is significantly less due to both the reduced quantity of engineering materials required and the fact that it is largely made of non-strategic and recyclable steel. Long term cost is considerably lower too, a result of expected life-of-vehicle durability of the hydraulic machines and, potentially, of the structural accumulator components.

Payback times for the Digital Displacement® machines are significantly reduced, as these are proportional to the product of system efficiency and the sum of initial cost and operation and maintenance cost.

Artemis is working hard to commercialise its systems for vehicle use. It is committed to the vision of making cost-effective hybrid systems for commercial vehicles.

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