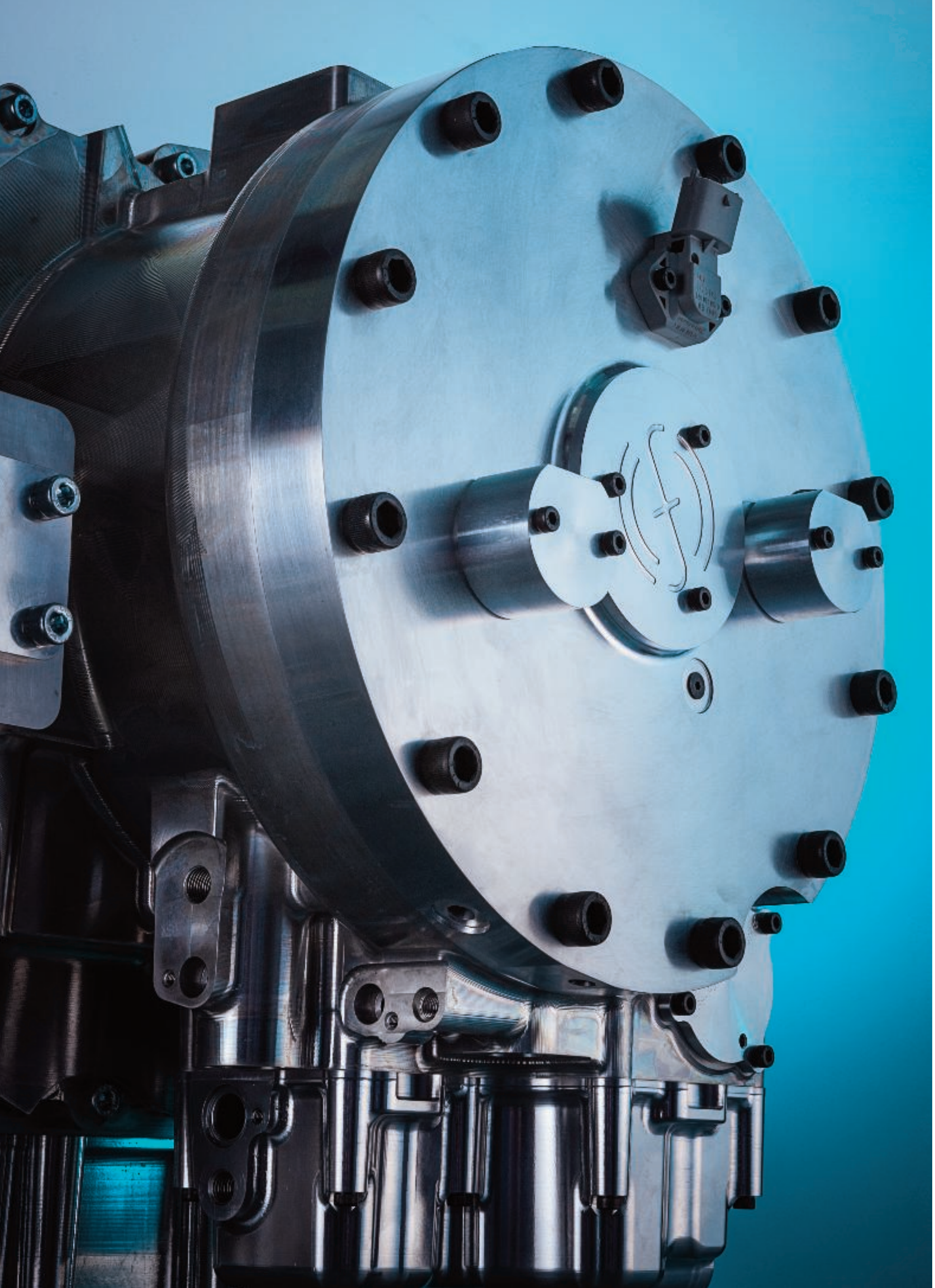
SPINNING WHEEL

Flywheels are among the simplest of devices ever considered for storing and regulating energy – but not when it comes to running them at 60,000 rpm. Brian Tinham reports on technology spinning off soon into commercial vehicles

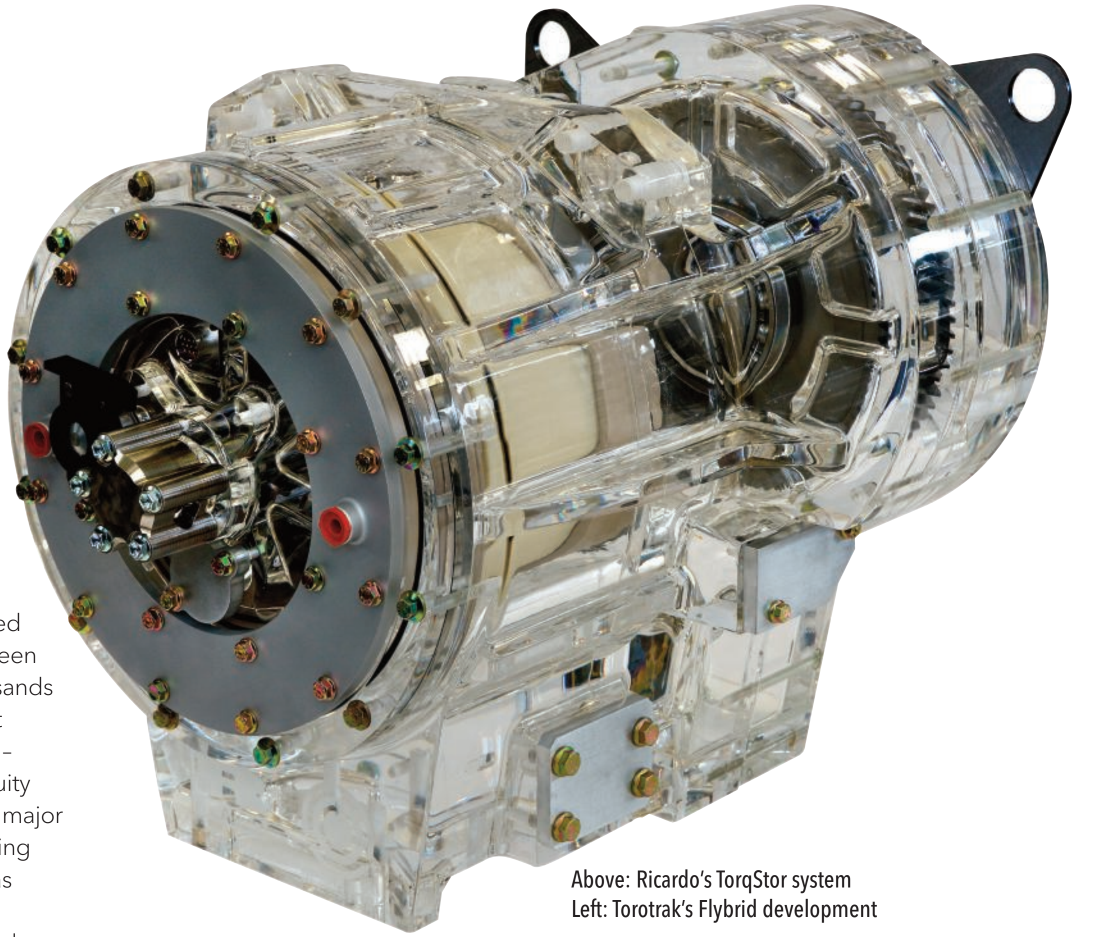


Often described as mechanical batteries, but with characteristics more closely resembling those of super-capacitors, flywheels are closer than ever to rolling into mainstream road transport. On the face of it, that's a strange assertion: records of flywheels in machines stretch back more than 1,000 years and they have been mainstays of steam engines almost since their invention – and latterly also internal combustion engines, regardless of fuel.

So, surely, these are neither novel inventions, nor old technologies condemned to wait in the wings for unforeseen applications? Indeed, but the point is that, to date, flywheels have been exploited almost exclusively for their ability to regulate rotational speed, harnessing what can best be described as their rotational inertia, or, if you prefer, angular momentum.

However, the flywheels we're getting excited about today draw upon their complementary property to store – albeit only for short periods – vast kinetic energy, and then release it to vehicles' drive wheels on demand in a controlled fashion to assist with acceleration. We're talking about mechanical, as opposed to electrical, KERS (kinetic energy recovery systems).

Granted, the physics remain the same: in the end, all flywheels store kinetic energy in proportion to the square of their angular velocity and radius (the latter determining moments of inertia). But the new function's focus is profoundly different. And so, accordingly, is the mechanical engineering required to deliver it.



Above: Ricardo's TorqStor system
Left: Torotrak's Flybrid development

Hence the observation that flywheels as now conceived are recent in concept, ingenious in execution – and just around the corner for commercial vehicles.

So let's take a look at two quite separate developments: those of Torotrak's Flybrid and Ricardo's TorqStor. Both rely on flywheels' fundamental dependence on speed squared to store power, so have been designed to rotate at tens of thousands of rpm. To minimise drag and heat losses, each also runs in a vacuum – which is where much of the ingenuity comes in. And, since mass is not a major contributor to energy capacity (being only linearly proportional), each has been engineered for low weight.

That sits well with potential vehicle operators fixated on payload, and it confers the engineering advantages that flow from relatively small, low-torque rotating components – including small gyroscopic forces. But that's where the similarities end.

FORMULA ONE

Flybrid first, and Torotrak sales and product development director Jon Hilton is the driving force here, having masterminded the project since he started Flybrid Automotive in 2007. That move followed his exit from Renault F1 after 17 years in motorsport (his formative years were in helicopter engine design with Rolls-Royce Aerospace), in the wake of the 2006 rule change prohibiting engine enhancements.

"We were making our engines go 5% faster every year and had been considering KERS. But when all that stopped, Doug Cross and I had a novel idea and started our own business," he recalls. That idea was a fully mechanical direct-drive KERS that, at a stroke, would eliminate any reliance on the cost, complexity and weight that arise from high-power electrics, electric-hybrid technology and batteries. But it wasn't without its challenges.

"Among the key issues we had to overcome was how to run the flywheel in a vacuum," states Hilton. "Yes, we could maintain an evacuated chamber using an internal vacuum pump, but we had to prevent air ingress via the spinning flywheel shaft, even at 60,000 rpm. So we developed a rotating seal mechanism, which has since joined our 60 patents, along with the vacuum pump, bearing lubrication system, etc."

Interestingly, those bearings are off-the-shelf hybrid units, selected for their steel race and ceramic balls. They don't fail, because they run outside the vacuum chamber – not subjected to temperatures and pressures of 100°C and 1mbar – meaning Flybrid can also use conventional oils without risk of boil-off. That pragmatic engineering typifies every aspect of this KERS development.

Hilton is reluctant to provide too much detail, but says: "Everything is designed and manufactured in-house: the gearbox, clutches, even the splined shafts and the rest of the transmission – as well as the pumps, electro-hydraulic controls and the software. And he insists that this approach has been vital to building a system that not only works efficiently and cost effectively, but is also bullet proof.

So far, so good. How about TorqStor? David Rollafson, Ricardo's vice president of global innovation and TorqStor project director, explains that this also had its origins in Formula One and at much the same time as Flybrid. It was never used in anger, but Ricardo kept the concept under development and, although faced with precisely the same engineering challenges, two years ago went public with a very different solution to Torotrak's.

Its designers had gone for a robust, permanently sealed vacuum chamber containing the flywheel – meaning no pump or rotating seal – with the torque then transferred via close-coupled magnets. "Our flywheel has a set of magnets embedded in the outer edge matched by magnets outside the chamber on the drive cup," explains

"If you installed a 25kg flywheel on a truck, you could comfortably get 1,000bhp"
Jon Hilton, Torotrak

Rollafson. Making that work has been challenging, he concedes, with much of the effort revolving around materials science and magnetic control.

The result: TorqStor's outer casing is fabricated from aluminium, while the vacuum cartridge itself is 10mm rigid composite. Inside the vacuum chamber, static ferrous pole pieces form a central magnetic gear, interacting with the rotating flywheel magnets on the inside and those forming the drive coupling on the outside.

"Think of it as a magnetic version of planetary gears in an epicyclic arrangement, with the magnetic flux rotating around the poles," suggests Rollafson. As for the flywheel itself, that comprises two parts – a shaft and hub made from nothing more fancy than high-speed gear steel, and the circumferential magnets, electrically isolated from the steel. Given that the flywheel is designed to rotate at 45,000 rpm, the magnets are retained in place by carbon fibre filaments.

Complex? Yes. Esoteric? Actually, no. And by applying industrial design techniques to this prototype, Ricardo has come up with a modular system capable of storing 4.5MJ by the simple expedient of expanding the sealed housing and extending the spinning axle to accommodate a secondary simple carbon fibre flywheel, also in the vacuum. Sizing this latter mass is then about using a software design tool in combination with an assessment of the vehicle application – the point being that you can never recover more than the energy available to harvest. And as for maintenance: the whole capsule is removable as a bolt off/on service replacement item.

POWER TRANSFER

Moving on to the power transmission method and control system, Rollafson explains that there are several options, depending on duty cycle (constant or variable speed/torque output, auxiliary or drive power, etc) and the drivetrain configuration. That might involve using a variator to mitigate for decaying flywheel speed – in Ricardo's case, a variable displacement pump motor for off-road vehicles, or a CVT (continuously variable transmission) for on road. Alternatively, the company has investigated using motor-generators with power electronics, although that clearly adds to the costs. Whatever the engineering selection, the control system then has to be tuned to the precise requirements.

So much for the engineering design. Turning to applications, Ricardo has focused initially on the off-highway and rail industries. "We bought an excavator, disassembled its hydraulics, built in the KERS flywheel and then reassembled it with our own controls to demonstrate a working vehicle. That was important, not only because potential users want to see the real thing and assess real fuel savings, but also because we needed to demonstrate that a hybridised system could maintain its 'feel' for professional excavator drivers," says Rollafson.

So Ricardo's excavator has spent the last 12 months digging sand, gravel, etc, and providing evidence that flywheels save money. "Now we're working with tier one suppliers and OEMs who will hopefully be taking our systems and building them in volume for the off-highway plant market."

As for the rail industry, development to date has been under an InnovateUK (formerly the Technology Strategy Board) project with Bombardier and Artemis, together building a rail simulator. "To go further, we'll have to adapt a locomotive with our KERS and implement a new control design – and we may have a few announcements to make shortly," smiles Rollafson.

What about Torotrak? Hilton explains that, like Ricardo, interest in Flybrid

The first Wrightbus StreetLite bus fitted with Torotrak's Flybrid KERS has gone into full-service trials with Arriva, in Gillingham, Kent. Photo: Chris Sharp

started in motor racing, with Honda, Jaguar and Volvo among big names signing up to early projects. However, the focus has since shifted to buses and off-road vehicles, with Wrightbus and JCB (the latter also under an InnovateUK project, with £7.3 million funding) going public. Indeed, back in March, Wrightbus announced that its first Flybrid KERS StreetLite bus (pictured above) had gone into full-service trials with Arriva in Gillingham, Kent.

That system, developed with Arriva, Productiv and Voith Turbo, was fitted in parallel to the transmission on the driveline and linked directly to the rear axle by an additional prop shaft. It also communicates with the vehicle's transmission to manage shifting and engine torque-down to achieve synchronisation and gain the fuel benefits when the flywheel is providing motive power.

Wrightbus engineering director Brian Maybin reveals that this project began two years ago, stating that tests on a retrofitted Arriva bus at the Millbrook test chamber had been "very encouraging". He reckons that "significant" fuel savings are available – enough to give bus operators a five-year payback, which is way better than the 12 years typically achievable with diesel-electric hybrids.

Is that realistic? Hilton is unequivocal: if the duty cycle involves urban driving, then absolutely yes. "It's not about stopping at bus stops: it's variations in running speed that are most worthwhile, because energy stored is proportional to speed squared. Unlike electric-diesel hybrids, we capture much more energy as vehicles slow from 30 to 25mph under normal driving conditions, than we do from five to zero."

150BHP FROM 8KG

That fact alone points to the sheer potential for flywheel-based KERS across other urban vehicles. Another is that the Wrightbus-Arriva system is capable of delivering 150bhp for short periods, yet the flywheel weighs just 8kg. "Batteries will never touch the power-to-weight ratio of flywheels," enthuses Hilton. "Admittedly, power delivery is short-lived, but if you installed a 25kg flywheel on a truck, you could comfortably get 1,000bhp."

Incidentally, reaction times are also extremely fast – from zero to full torque in 12msec and back to zero in 9msec. "So we can easily react to instantaneous throttle demand by ramping up torque ahead of turbo lag, so avoiding fuel-rich spikes on the engine when it's at its least efficient,and minimising tailpipe NOx and particulates." And you can see the scope for remapping engine strategies vehicle by vehicle not only to reduce fuel consumption, but also to slash emissions at the micro level.

Hence the existence of several demonstrator vehicles on behind-the-scenes trials now, says Hilton, and not just buses – although he is reluctant to name participants. "KERS packages designed for buses can fit more or less straight into trucks – just outside the chassis rail, and with the KERS prop shaft driving through a pillar bearing into the differential. That would be pretty universal for long wheelbase trucks, such as RCVs [refuse collection vehicles], but also delivery trucks on urban duties."

When can we expect series production? Hilton says Torotrak will be shipping Flybrid KERS packages for buses next year and that trucks will be next. "We have been talking to truck manufacturers for some time. This will be a good application behind Wrightbus." TE