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The NorEaster uses two concentric output shafts to drive counter-rotating propellers, negating the need for a tail rotor (All images courtesy of Peter Casey, O'Neill Power Systems)

A question of timing

Rory Jackson examines the development of this radial engine for helicopter-type UAVs that uses a cam-based mechanism for its drive transmission

O'Neill Power Systems is a start-up company based in Fall River, Massachusetts, which has developed and patented a unique propulsion solution with great potential for helicopter-type UAVs. Its NorEaster engine was originally conceived by company CEO Jim O'Neill, and has been further developed by Bob Norton, an engineering professor from the Worcester Polytechnic Institute (WPI) in Massachusetts, who has since become O'Neill's chief engineer.

It is a four-stroke, 80 hp radially arranged eight-cylinder reciprocating unit. It has two output shafts, integrated coaxially, to drive two counter-rotating propellers. Opening the engine housing reveals a drive transmission system that relies not on a crankshaft or turbine but on a cam-based mechanism that is unlike anything seen elsewhere.

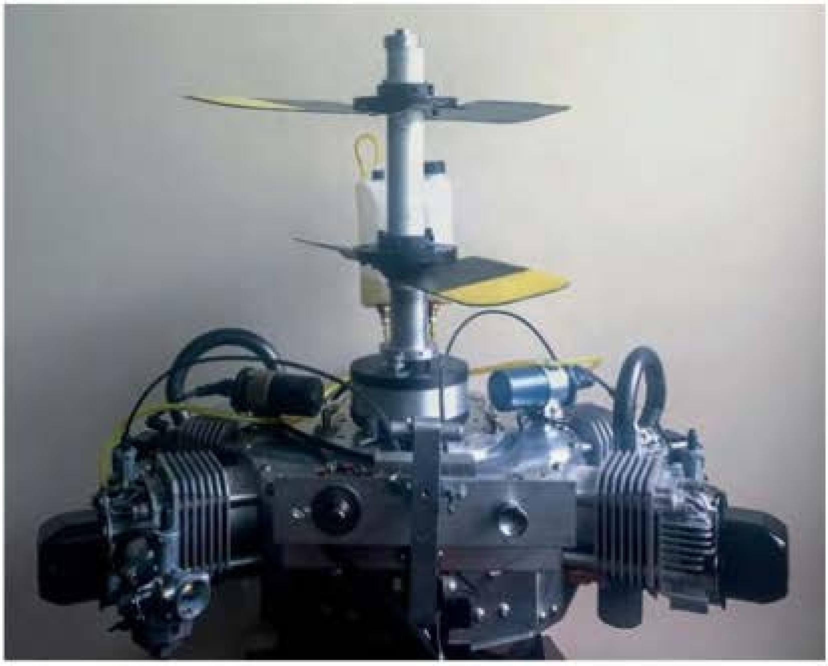
Rather than being developed to target one or two specific engineering problems or requests from UAV operators, the NorEaster is designed to replace existing helicopter drive systems entirely, thus resolving the myriad issues associated with them.

The NorEaster's history

The CEO's inspiration for the engine came to him in 1969, when he was stationed in South Korea on military service.

"Although I wasn't a helicopter pilot, I spent a lot of time on helicopters, just as a lot of my associates were doing in Vietnam," O'Neill explains. "What I noticed back then about conventional helicopter designs is that the tail rotor is incredibly vulnerable. Even if you're well-clear of enemy combatants, it's so easy for the rotor to get knocked and disrupted by the branch of a tree or some other obstacle."

The tail rotor is also a significant source



The engine is currently in its fifth prototype, which initially entered dynamometer testing about a year ago, starting with a version featuring four cylinders

of the considerable work that goes into helicopter drivetrain maintenance, and the cause of a great number of crashes. These flaws drove much of the motivation behind the NorEaster's development.

Related to the tail rotor are several other issues that the conventional helicopter powertrain is subject to, which O'Neill wanted to address. "On almost all helicopters, you start with an engine, typically a turbine engine for larger helicopters, the output for which has to go through a highly complex transmission system with a reduction in two directions – one for the lifting rotor, one for the tail rotor," he says.

Helicopters typically require rotor lifting speeds of between 500 and 1500 rpm, compared with the typical turbine speeds of 10,000-20,000 rpm.

Norton says, "Those transmission reductions are one of the most problematic technologies in aviation, purely in terms of maintenance requirements. They require persistent care, they often fail, and when they do it's often catastrophic, because you then have a helicopter in the air with no lift. Without a pilot well-versed in autorotation, that helicopter is going to hit the ground extremely hard."

The NorEaster effectively eliminates that transmission, because the cam-drive system gives an automatic, internalised reduction ratio, equal to the number of lobes on each cam.

And since it has been designed with two counter-rotating output shafts, there is no need for a tail rotor to counter torque – each propeller cancels the other's torque reaction, as well as almost the entirety of each other's vibration.

A conventional helicopter powertrain also takes up a significant proportion of aircraft weight. As indicated, it requires a number of dedicated structures and gearboxes, as well as gearing systems to keep the engine's centre of gravity stable.

"So we wanted something that was more like an outboard motor for helicopters," O'Neill says. "It's a single, fully integrated turnkey unit, with no need for a complex transmission system. You just bolt it on to whatever you want to fly, and it uses a fraction of the parts and weight of a conventional helicopter transmission, which is critical for the viability of UAVs in particular."

It was around 1999 that O'Neill first conceived the idea of a cam-driven engine. "I made a couple of crude prototypes," he recalls. "Soon after, through a stroke of luck, I met Bob Norton, who had written several books, including one on cam design and had taught at WPI for more than 30 years. He examined the cams I had designed and tested, and became a key partner in the design and development of the NorEaster engine."

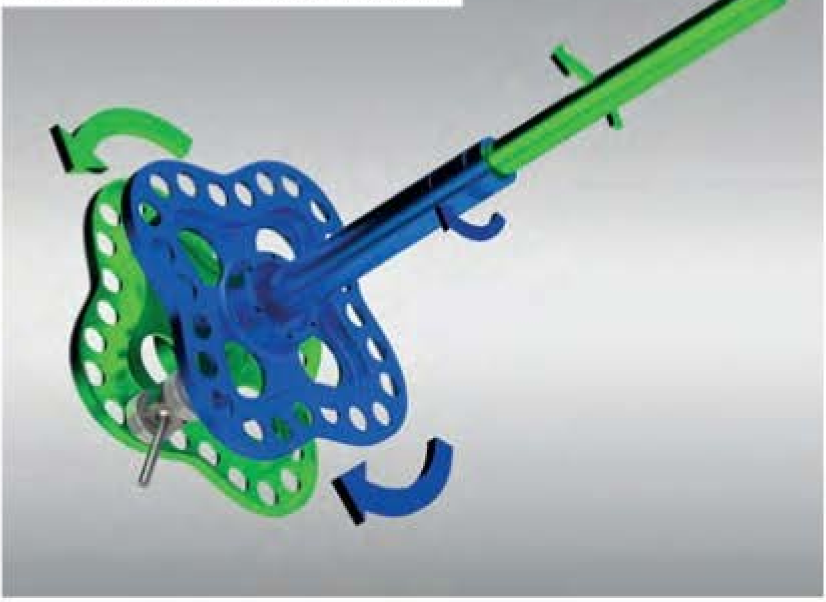
Their collaboration quickly led to a third prototype, which used a four-stroke power cycle and featured two counter-rotating output shafts, one extending from the top of the engine and the other from the bottom.

After testing and demonstrating that model, development of the engine was moved to WPI. With the help of two teams of mechanical engineering students, a fourth prototype was designed. That two-stroke version had an improved cam drive design to provide the revs and reduction ratio that O'Neill and Norton were looking for.

"Further improvements on that led us to the version we have right now – our fifth prototype, a four-stroke 80 hp engine, with some dyno testing done to validate that the design performs exactly as we've been aiming for," O'Neill says. "The next step would be to do a lift test, and that will be the last step, pending further development with partners and end-users."

Development of the current version began two years ago, with the first dyno test following a year later. Significant input into it has also come from Bob Anderson, founder of OceanServer Technology, an AUV manufacturer also based in Massachusetts.

The decision to revert to a four-stroke cycle came partially from O'Neill and Norton's automotive engineering backgrounds, which made them more familiar with such technology, and



The NorEaster is a reciprocating engine that integrates a counter-rotating cam-based drive transmission instead of a conventional crank-con rod arrangement

from not being able to get the speed and horsepower they wanted (although the engine ran with vibrations as low as they hoped for).

"In my opinion, the stroke cycle is irrelevant," Norton says. "If you can make a two-stroke cycle work on this engine, you'll get as much power as you would from a crank engine."

Many of the components and much of the ancillary engine systems surrounding the drive and transmission are COTS products, having been selected principally for cost-effectiveness. The main aim of development has been to iterate and optimise that patented transmission across each prototype, rather than develop costly bespoke subsystems to maximise the performance specifications.

With the minimal vibration, secure reduction ratio and low maintenance requirements of the drive transmission system – especially when compared with helicopter powertrains – as core selling points, O'Neill Power Systems has made it clear that the various supporting systems are bound to improve in the future.

As the company is actively seeking partnerships for the NorEaster's further development, its engineering team is open to input on what the exact nature and form of those improvements will be. Their own future objectives include an aviation-grade ECU with electronic fuel injection and an improved ignition system.

At the moment, O'Neill Power Systems is located at the University of Massachusetts Dartmouth Center of Innovation and Entrepreneurship, where professors and students contribute to the engineering and business development as well as other aspects of the company. Much of the ongoing work on the engine is overseen (and aided) by Edward Spring, laboratory manager and mentor at UoM Dartmouth.

Cam drive and transmission

The NorEaster weighs 91 kg, with dyno tests thus far indicating a peak power output of 100 hp (75 kW). The system measures 92 x 92 x 30.5 cm, not including the output shafts, which will vary in length depending on the end-user's vehicle and the flexibility of the rotor material they have selected.

Its speed is in the 1000-2000 rpm range. Maximum torque output is 950 Nm, with 760 Nm produced during normal operations and is dependent on the design of the combustion cycle and its components.

O'Neill estimates that this degree of power and torque could enable a helicopter UAV incorporating the NorEaster could carry up to 450 kg of payload, making it particularly applicable for aerial logistics, urban air taxis and other heavy-lift missions.

The inside of the engine contains two chambers which are symmetrical in the horizontal axis. Each chamber contains one drive cam – a four-lobed arrangement resembling a four-pointed star, designed to be push-actuated by the NorEaster's pistons.

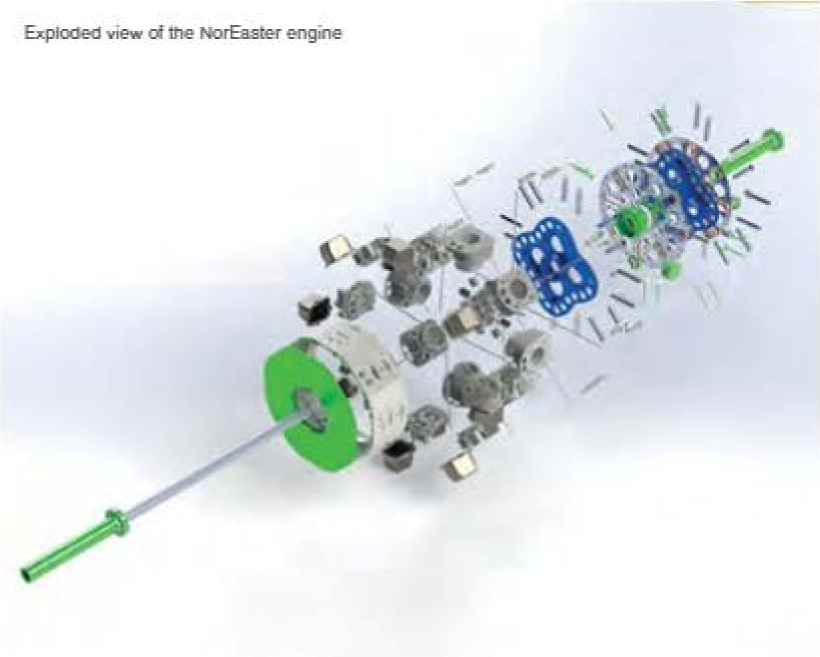
Both output shafts extend upwards through the engine, with the lower chamber's drive cam's narrower shaft threading up through the wider shaft mounted on the upper chamber's cam. Each drive cam is also oriented to rotate in the opposite direction to the other, to provide the counter-rotation of the propellers.

The eight cylinders and pistons are oriented radially and co-planarly around the eight external surfaces of the 'cam case'.

Rather than comprising a conventional head and pin to attach a con rod's small end, the NorEaster's piston heads have a fixed 5 cm rod extending from underneath them, into the cam case. At the bottom of the central shaft comprising most of the piston rod is a perpendicular cross-member.

As the pistons move up and down, their linear motion in the cylinders (and the absence of transverse forces in the cylinder from con rod oscillation) is maintained by keeping the rod cross-members slotted within a guide plate.

The cam case contains two of these guide plates – one for the pistons' upper cross-member halves, another for



Exploded view of the NorEaster engine

the lower halves – with straight-line slots running between the centre and outer parts of the case for the cross-members to run in. Mounted on each cross-member are four ball bearings, with the outermost being around half the diameter of the inner bearings.

The drive cams and pistons are oriented so that when the piston head fires downwards (towards the centre of the engine), the larger ball bearings on the cross-members push down against the two separate cams in their respective engine chambers. Each bearing rolls against its cam's downward-sloping surface, to push them apart.

From above, this effect looks rather like scissor blades being opened by a round metal object pushing into them and forcing them apart. By this method, rotational momentum is given to the drive cams, the linear motion of the pistons being converted into rotational motion for the output shafts and propellers.

After pushing apart the downward-sloping cam surfaces and reaching the cams' bottom dead centres (BDCs), the piston is then driven back up into its cylinder for the exhaust stroke, by the immediately following upward slopes of the cams, which carry forward their rotational momentum and push up against the large bearings.

To ensure the piston is carried up steadily, an additional, downward-facing cam surface is designed along the opposite inner rim of each driving cam. This effectively creates a raceway between the cam lobes and the rim, and helps the overall efficiency of the system by ensuring that no kinetic energy is 'lost' as the pistons and cams push each other up and down.

The smaller bearings fixed to the outer part of the piston rods' cross-members run along and against this upper rim. The reason for that is to prevent the need for the larger bearings to run within this raceway – doing so would mean the upper and lower tracks of the raceway acting on the bearing in opposite directions. That could cause the large bearing to spin in both directions and generate unnecessary friction, meaning more oil would be needed and negating the reason for having rolling bearings in the first place.

Once the cross-member bearings reach the top dead centre (TDC) of the next lobe (for the cylinder's next intake stroke), the next cylinder along fires and pushes the cams, with the upper track of the cam raceway then pulling the first cylinder's piston down to draw in the fuel-air mixture.

Typically, in the NorEaster (with the four-lobe drive cam), four of the eight pistons stroke downwards at once. One opposing pair of cylinders will be firing, while the other pair will be taking in fuel and air. As this happens, the other four pistons are being pushed upwards for compression and exhaust.

Once the first four pistons' cross-members reach the BDC of their respective cam lobes, and the second four have reached TDC, they alternate their movement, with the first four now stroking upwards as the second four stroke down.

By having two horizontally opposing cylinders firing on each stroke, the directional force of each cylinder's combustion is cancelled out, reducing engine vibration. The firing order of the cylinders follows clockwise around the engine when viewed from above, with an even firing time between them. This means that, initially, the first and fifth cylinders will fire, followed by the second and sixth cylinders, and so on.

It follows from this that each horizontally opposed pair of lobes corresponds to similar halves of the power cycle. Going around the cam, the first and third lobes' surfaces contact the piston bearings during their exhaust and intake strokes, while the second and fourth lobes correspond to the compression and combustion phases.

All these contacting surfaces and bearings mean oiling is crucial. "In its current design iteration the oil pump is external, but we hope for the production model to integrate the pump inside the cam case," O'Neill comments.

"Right now, the cam case itself is also the oil pan, so oil is pumped up at the top of the driving cams, with gravity and centrifugal motion providing for the

Anatomy

NorEaster helicopter engine
Radial eight-cylinder, four-stroke
Naturally aspirated
Carburetted
Weight: 91 kg
Size: 92 x 92 x 30.5 cm
Maximum power output: 100 hp
Operating power output: 80 hp
Maximum torque: 950 Nm (700 lb-ft)
Operating torque: 760 Nm (560 lb-ft)
Bore: 6.826 cm
Stroke: 5.588 cm
Displacement (per cylinder): 205 cc
Total displacement: 1640 cc
Compression ratio, 8.5 to 1
Compatible fuel types: petrol
Operating speed: 750 rpm

Many of the NorEaster's key components, including the guide plates, were CNC-machined from aluminium

The NorEaster's cam case comprises seven main components. An eight-sided cam housing forms the main structural block, with the inner side being cylindrical and featuring a rim running around the middle.

The cam housing is CNC-machined from an aluminium billet. While no coatings are currently used, future versions might be anodised for corrosion resistance. Piston rod apertures are then drilled radially inward at the centre of each of its eight faces.

Next, two circular guide plates are installed inside the cam housing. These are also CNC-machined aluminium with potential for anodising, and each plate is fastened to one side of the cam housing's inner rim, with 32 M25 fasteners.

Eight slots are cut axially into the guide plate to the same length as the piston stroke, with a central aperture for the output shafts and main bearings. Sixteen additional holes are cut into the guide plate for cooling and reduced weight.

The engine has a pair of four-lobe (38 cm at maximum diameter) drive cams machined from plates of hardened steel and coated using a proprietary method and material, with one over each guide plate. The concentrically arranged output shafts are machined separately from hardened steel and welded on afterwards.

It also has four main ball bearings, two on each shaft – two in the space between the output shafts, and two between the shafts and housing covers to hold the drive cams in place.

A tool steel valve cam for driving the intake and exhaust valves is bolted using six fasteners atop the upper drive cam, around the wider output shaft.

After the cam case's sides are ground to accept the pistons and cylinders, eight COTS aluminium cylinders with Nikasil inner coatings (cylinder heads machined in-house, also from aluminium) are fastened to each of the eight sides, using four M10 fasteners each.

The pistons are also machined from aluminium, with three rings about the piston head. The top two are compression rings, with an oiling ring underneath. A piston rod 5 cm long extends from under the head, with a cross-member extending from either side and mounting two pairs of ball bearings for contacting with the drive cams.

The cam case is closed on either side by a pair of housing covers. These octagonal aluminium plates might also be anodised for added corrosion resistance in future versions of the engine. Each housing cover is bolted to an opposite opening of eight-sided cam housing using 32 M8 fasteners and 18 M32s.

distribution of the oil across the cams, all around the cam case, and to the bearings, piston rods and oil rings. The oil eventually settles at the bottom of the cam case, where it is then recirculated, with no losses as the system is fully closed."

In the NorEaster's current iteration, cooling is provided by the downward thrust of air from the propellers, which flows over the outer surface of the cam case and across the cylinders.

The number of lobes on the driving cams may be subject to change. The primary aim of the engine's design is that the output shafts move at between 750 and 1250 rpm, as befitting a helicopter rotor system.

As the cylinders and pistons were originally designed for four-stroke operations at 4000 rpm, the cam currently has four lobes to provide a four-to-one reduction ratio. Accomplishing this reduction without belts or gears means the engine avoids all the inherent maintenance issues and points of mechanical failure that helicopter transmission systems are prone to.

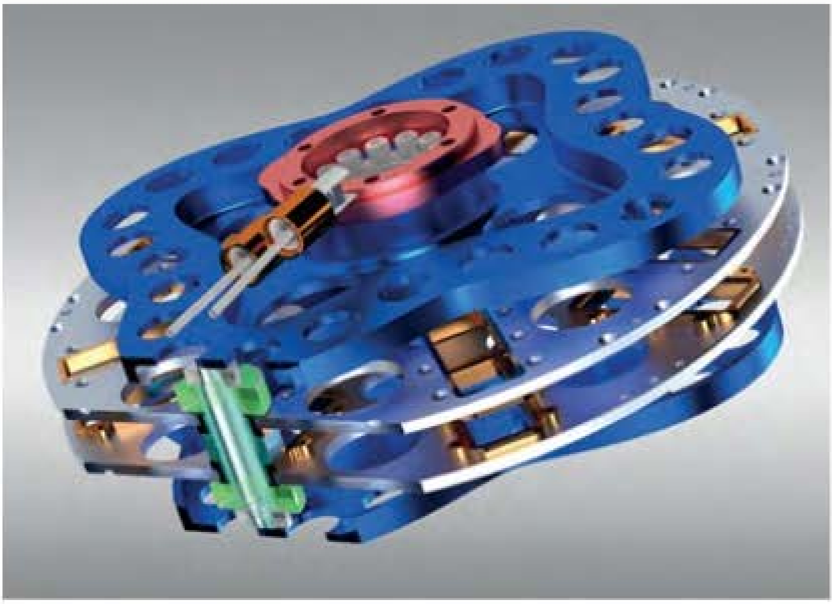
"I designed all the cams using my own cam design program, Dynacam," Norton explains. "The cam profile data from Dynacam was then imported into CAD programs to generate the cam surfaces."

Valve control

As the current configuration of NorEaster uses a four-stroke power cycle, the cam-driven engine has been designed with a series of components to form a secondary cam system, which acts as the power system's valvetrain.

"The valve drive system is so simple on this engine, compared with what you'd usually find on an automotive or UAV four-stroke," Norton comments.

The heart of the valve control and timing is a valve cam. That is the effective 'camshaft' of the NorEaster, although it is much wider than it is long (and therefore more closely resembles a pair of coupled rings than a shaft), and does not need any timing belt or chain to operate the valves or keep accurate timing.



Within the (blue) drive cam's raceway, the large bearings (green) on the piston rod's cross-member push down on the cam's inner lobes, while the smaller bearings (grey) on the outer part of the cross-member are pushed up to run against the outer lobes

That has allowed the overall valvetrain to be designed in line with O'Neill's philosophy of avoiding belt-oriented transmissions. Its design features two cams, set on two tiers with two lobes each, each cam's lobes being set opposite to each other.

In this arrangement, one cam actuates the cylinders' intake valves while the other is fixed to operate the exhaust valves. As each valve cam has two lobes, compared with the four on the drive cams, each valve is opened and closed in order as well as once per power cycle, with timing fixed by the fact that the upper drive cam is directly driving the valve cam.

Put more simply, just as two power cycles (or eight strokes) are completed for every rotation of the drive cam, so each valve will be opened and closed twice for every revolution of the output shaft.

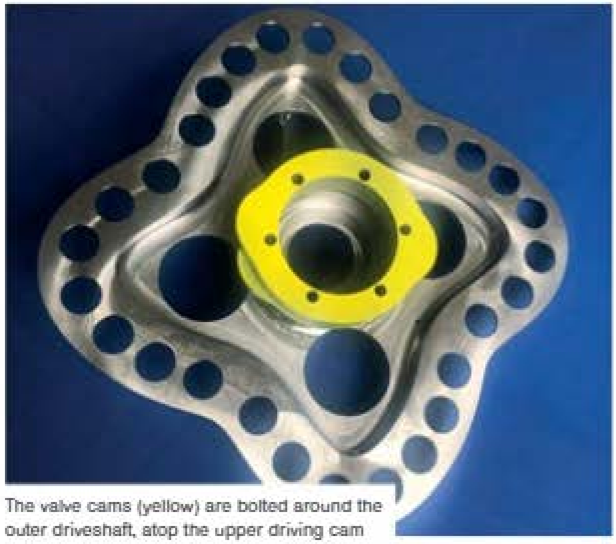
To actuate an intake valve, the valve cam's first upper lobe comes into contact with a roller lifter, eight of which are arranged about the path of each lobe (for a total of 16). The lobe pushes the roller lifter upwards, which lifts a 22 cm pushrod up against the input end of a rocker arm.

The output end of the rocker arm thus rotates downwards, pushing down against the spring-loaded intake valve and opening the port to the carburettor's fuel-air mixture. As the zenith of the valve cam lobe passes, the roller lifter and pushrod are lowered down again, and the valve lifts upwards to seal the intake port with the valve seat.

After the combustion phase, the second valve cam comes around to set in motion a largely identical procedure to open and shut the exhaust valve. While each valve cam's lobes are set 180º apart, the exhaust valve cam is offset slightly so that each intake lobe's corresponding exhaust lobe follows slightly faster, at about 144º.

The intake valve seat (and by extension, the intake port) is 2.6975 cm in diameter, while the exhaust valve is 2.22 cm across. Both ports are placed atop each cylinder, equidistant from the centre of the bore, with a flat valve angle (0º) between them.

Each valve cam (pink) pushes up against the lifters (gold) to actuate either the eight intake valves or eight exhaust valves, via a linkage made up of pushrods, rocker arms and spring-stems



The valve cams (yellow) are bolted around the outer driveshaft, atop the upper driving cam

A round steel tube extends upwards from the exhaust chambers atop the cylinder heads, before turning 180° to funnel the exhaust fumes down between the cylinders. "We've also equipped it with mufflers from Briggs & Stratton, to reduce the noise generated by that eight-cylinder system," O'Neill points out.

"Originally the cylinder heads had the exhaust directed to the top, but we didn't want that flowing near the rotors, so we redesigned it to direct the fumes below where they'd be less harmful."

On the current prototype, fuel is stored in a gravity-set fuel tank, with separate hoses extending from it to the carburettors on each cylinder head. Each carburettor has its own throttle body for air intake control.

Cam engine versus crank/con rod engine

As well as improving over helicopter turbine-and-belt arrangements, the NorEaster's cam-based drive system is designed to provide certain advantages over the more conventional reciprocating engine's crankshaft-based drive.

In a crank engine, each con rod's big end rotates with the motion of its crank pin, while the small end of the con rod, being fitted to the piston pin, generates a secondary 'side-to-side' harmonic.

That can create friction and wear between the piston and its cylinder wall, by pulling to one side during its downward stroke and to the other during the upward stroke.

The NorEaster's pistons are not pulled side to side in this way, as the drive cams exert balanced forces on either side, and the guide plates hold the cross-members in place to prevent the pistons being 'twirled' in either direction.

Also, as mentioned, the radial operation of the NorEaster with the cylinders firing in opposing pairs means all the harmonics of the inertial force generated by combustion cancel each other out.

"The co-planarity of the cylinder distribution about the cam case also means there is no inertial shaking moment," Norton says. "And again, the counter-rotation of the output shafts and propellers cancels the reaction torque, making for a minimally vibrating power output."

The future

In addition to welcoming engineering input from future partners and end-users, O'Neill Power Systems envisages several other configurations of the NorEaster.

One, designed for UUV propulsion, uses an electric motor as the main power source driving the lower cam, with the cylinders removed and the piston rods held in their slots to actuate the upper cam and its output shaft.

This alternative use case for O'Neill's drive transmission system is titled the VorTaq. "UUVs are mostly electrically powered, with one propeller, so they need control fins which are constantly adjusting to compensate for the dynamic roll the prop induces, to stay level and flat to generate quality sonar imagery," says Anderson of OceanServer Technology.

"The counter-rotating propellers would induce no roll, so you could reduce those control fins significantly, meaning fewer potential points of mechanical failure and much less drag on the vehicle."

A future version might also integrate a tertiary output drive shaft, driven by a timed gear intermeshing with teeth formed on one of the drive cams. That would extend perpendicularly from the NorEaster, to drive a pusher propeller.

Whatever form the next engine takes though, it is undeniable that the technology at the heart of the NorEaster system has the potential to revolutionise the next wave of UAVs and their markets. □