Should we be contrary?

For electric propulsion, one British company is certain the answer is yes

By: Nick Sills*

Few would disagree that electric propulsion has a big part to play in the future of aviation—as it does in the car industry. Yet, while a number of developers have installed and tested electric motors in place of piston engines in several types of light aircraft, few have realised the immense benefits that the change from combustion engines to electric motors could bring to the design and performance of light aircraft propulsion systems.

Simply swapping a piston engine for an electric motor in an aeroplane will not fundamentally change the performance: in a propeller-driven aeroplane it is the prop that dictates performance far more than the engine. Exchanging the traditional single propeller for a pair of contra-rotating (CR) ones, however, can significantly increase the capabilities of the propulsion system and an aircraft's performance. This is because the CR format counteracts 'swirl', giving yaw-free thrust (similar to a jet engine), improves acceleration, and offers a higher top speed compared to a single-propeller driven by an electric or combustion engine of the same power.

Driving each propeller with a separate motor further improves performance and confers 'twin engine' safety. Certain types of electric motor offer an extraordinary opportunity to construct a simple, inexpensive contra-rotating propulsion system for general aviation.

One of the companies looking at this, Contra Electric Propulsion Limited, has designed, built and ground-tested a complete twin motor contra-rotating propeller system. From the results achieved, the company believes that the CR format will become the new standard for high performance sport and aerobatic aircraft. It will also be ideal for companies operating aircraft from water, snow or ice, and in mountainous terrain, where performance is often far more important than range.

The company plans to install and flight-test a pre-production 225kW (300hp) twin motor system in a Falcomposite Furio kitplane, and build an entry level 125kW (155hp) single-motor, geared system to be tested in a Super Cub floatplane. Options up to 1,000kW are being explored.

Proven technology

While contra-rotating propellers are commonly used to increase the performance of leisure and commercial marine craft, the concept has never been adopted in civil aviation, at least in the West.

In military aviation it has long been known that a pair of CR propellers provides significant performance benefits over a same-horsepower single propeller. In the late 1940s, '50s and '60s the format was used in many military aircraft to increase performance and allow vertical takeoff in some types. However, using piston and gas turbine power plants the arrangement proved incredibly complex and expensive to build, as variable pitch propellers and gearboxes had to be used to manage the engines' torque curves and speed. Now, developments in the automotive industry of advanced high-torque, slow speed electric motors, and associated power electronics set the stage for a revolution in light aircraft propulsion systems. For the first time fixed-pitch propellers and direct drives can be used, reducing the complexity and cost of a CR propeller system from a military budget to a civil one.

Developed too late to see RAF service, Martin-Baker's brilliant MB5 was one of the first piston-engine fighters to be fitted with contra-rotating propellers

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The benefits

Several benefits are anticipated from an electric contra-rotating, fixed pitch propeller propulsion system. Thanks to its swirl-free thrust, the resulting decrease in airframe drag alone (the drag caused by balancing yaw) makes the CR propeller set-up five to seven per cent more efficient in propelling an aircraft than a single propeller. Maximum power can be applied or reduced almost instantly with little effect on the aircraft attitude or trim, considerably enhancing aircraft performance.

For the first time in civil aviation it allows a 'twin engine' system to be mounted on the nose of an aircraft. This is possible because the annulus drive architecture of some high power electric motors allows a coaxial shaft arrangement to be installed centrally between two (or more) stacked motors and to directly drive the propeller shafts—no gears are required. And, although no legislation yet exists, it is thought that the coaxial arrangement of CR propellers will not require a pilot to hold a twin rating to operate the system: an engine failure would cause almost no asymmetric flight effect—as opposed to a wing-mounted engine failure, for which training has to be undertaken.

The number of benefits gained by using a twin electric motor-powered fixed pitch CR propulsion system over a same power single fixed or variable pitch propeller and piston engine system could almost be seen as too good to be true. They include:

- Twin engine safety and effective classification
- Simple, two-lever thrust controls and instrumentation
- Low impact on flight symmetry from an 'engine' failure
- No aircraft yaw during power changes
- Almost instant 'throttle' response
- Very powerful reverse thrust
- Shortened takeoff and landing runs
- Improved climb performance and higher top speed
- Propulsion system immune to icing
- No weight change during flight
- Smaller overall propeller disc diameter
- Extremely simple mechanical construction
- Virtually silent motor operation, with no exhaust pollution
- Very high energy efficiency
- No engine warming, shock cooling or spool up time
- Recharge using ground power, wind or solar sources
- No change in power output at sea level or high altitude
- No liquid fuel or lubrication system
- Offers aerobatic aircraft unique manoeuvring capabilities
- Negligible vibration
- Very low maintenance and operating costs
- TBO extended to 5,000 hours
- System can be retrofitted in many aircraft.

What's the catch?

One downside is the limited endurance and range using existing battery energy capacities. Inefficient as they are, hydrocarbon-fuelled engine systems have a range some six-to-eight times greater than an equivalent power and range electric system with the same total system weight. And it is likely to be up to ten years until electric range exceeds combustion range, system weight-for-system weight, by which time battery scientists say they will be able to construct batteries with up to three times the energy density of hydrocarbon fuels.

Initially, therefore, adoption of electric propulsion is most likely in aircraft where a huge improvement in performance is most beneficial and short endurance of 45 to 90 minutes between charges can be tolerated. In some types, electro-combustion hybrid systems may be an appropriate interim solution for longer range.

Another issue is the propeller. To realise the potential of electric motors requires the design and manufacture of a completely new type of fixed-pitch propeller, capable of providing high thrust both forward and in reverse, and able to absorb the much wider range of power available from electric motors. Whilst the maximum power available from a piston engine is rarely more than thirty per cent greater than its continuous rating, an electric motor is often capable of 100-200% over its continuous rating for short periods, sufficient to offer huge additional performance at takeoff and climb out. The 125kW (155hp) continuous rated CRPS destined for installation in the Super Cub float/ski plane will be capable of providing well over 250kW (310hp) for takeoff and initial climb, and reducing drastically the landing run on water, ice and snow.

Propeller development

The propellers to be used were developed with Hercules Propellers during an intensive eighteen month R&D programme, assisted by UK Government and NATEP funding. The research generated computer algorithms capable of calculating the shape, diameter, pitch, blade area, chord and other parameters from data inputs such as motor performance, aircraft flight envelope requirements and drag profile. The software generated →

BELOW: **first pass CNC machining of the wooden propellers**

'3-D' models that could be directly input to a purpose-designed CNC machine to manufacture propeller sets. A 'loss' process of propeller manufacture was chosen over other methods used for composites or metals, where expensive tooling is generally required. Laminated beech wood blocks (the 'original carbon fibre' as Rupert Wasey from Hercules puts it) were used as the base material from which the two-bladed propeller pairs were machined and finished by hand.

The two propellers were designed to be driven at the same speed and to absorb the same power, but as a contra-rotating pair they differ significantly in pitch, diameter, blade area and shape. The outer portion of each blade was given a symmetrical aerofoil allowing the propellers to generate both forward and reverse thrust.

Particular attention was paid to the manner in which two fixed-pitch contra-rotating propellers work together to generate thrust and in establishing their ideal spacing. The propellers are designed to be efficient over a wide range of speed from 1,800 (cruise) to 2,700rpm (max power) in order to absorb the motor's power delivery curve and offer a wide airspeed range.

A significant benefit of contra rotation is that as a two stage system it can raise the velocity of air significantly higher than is possible with a 'single-stage propeller'. Thus a single propeller driven aircraft designed for high speed 'maxes-out' at about 0.5 Mach whilst a similar aircraft with same power contra-rotating propellers maxes-out at about 0.6 Mach, some 0.1 Mach higher (0.1 Mach = 75mph). This is the reason the Tupolev 95 'Bear' aircraft is one of the world's fastest propeller driven aeroplanes.

Proving the design

In order to prove the propeller design and establish how they performed in a real world airfield environment, including ground operations, taxying and simulated takeoff and landing run performance, it was necessary to design and build a complete electric propulsion system and install it on a mobile test rig.

The unit has a coaxial propeller shaft assembly and motor cooling system. Considerable care had to be taken in designing the components to enable a workable assembly sequence, as the coaxial shaft assembly and bearings had to be designed to be installed through the motors and take axial loading in both directions during forward and reverse thrust tests.

The completed unit was mounted to a purpose-designed, fully instrumented test frame. The test frame was integrated into an electric vehicle with duplicated power packs, inverters, power electronics, wiring and controllers.

Potenza Technology Ltd., a Coventry based high tech automotive company specialising in electric vehicle propulsion, was awarded the CRPS detailed design, engineering and commissioning contact.

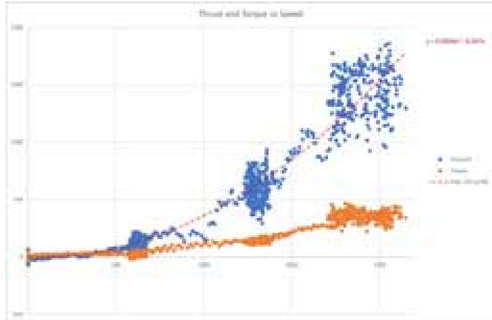
Two 125kW permanent magnet axial flux motors were bolted together in series and a coaxial contra rotating shaft assembly installed to transfer power from the rear motor to the front propeller and from the front motor to the rear propeller. An annular splined coupling within each motor delivers power directly to a spline on each shaft. There are no gears.

The vehicle and propulsion system were extensively instrumented and real time data recorded for thrust, torque (yaw), rpm, temperature and power consumption during static tests and additionally acceleration and speed during mobile test series on the runway.

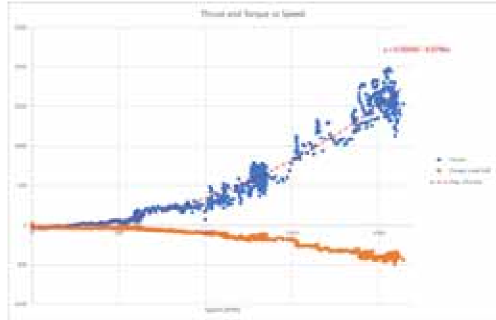
Video recordings were made to show the independent control of the propellers forward and backwards, in contra-rotation and each propeller separately and also to show the braking effect of reverse thrust to stop the vehicle and then back it down the runway—much to the amazement of passing aviators.

The static and mobile test program was undertaken at Gloucestershire Airport.

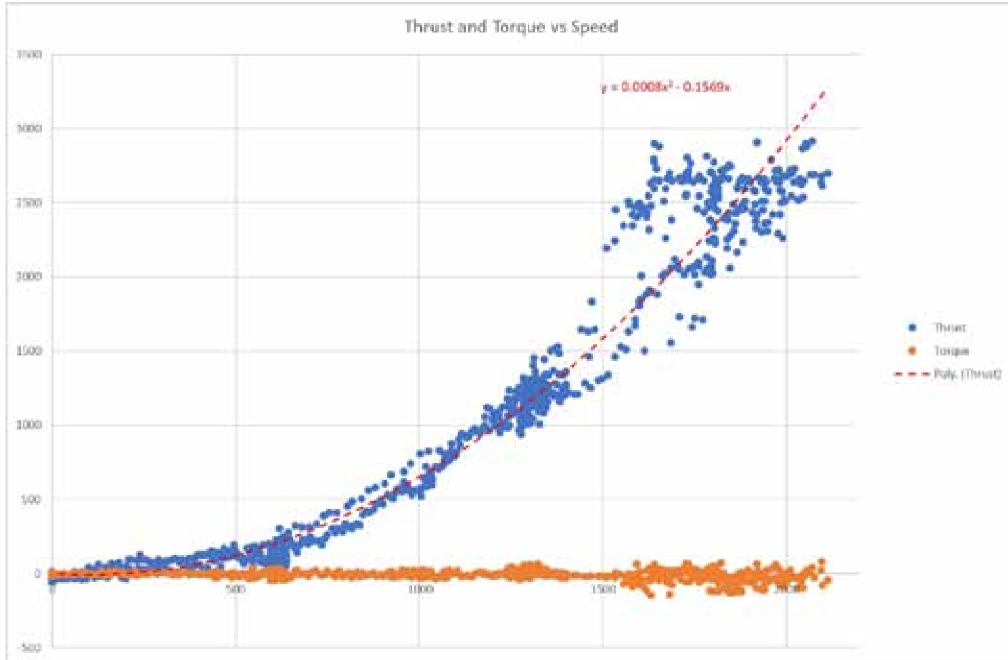
BELOW: **test vehicle with full CRPS system installed. The technician is calibrating system sensors array prior to conducting static tests**



Thrust (blue) & torque (orange), front motor



Thrust & torque, rear motor



Combined motors - net torque close to zero

Test Results

In tests the 1,200kg vehicle assembly (including occupants) was accelerated from standstill to 63kt IAS in 200m using 138kW (180hp) total power or 69kW (90hp) from each of the motors. This test was undertaken to compare the performance of a Furio aircraft fitted with a single Lycoming IO-360 engine rated at 180hp and three-bladed VP propeller with a takeoff weight of 1,200kg to that with an electric CR system of the same power. (The Furio's rotation speed, Vr is under 63kt.)

Static thrust tests from the piston powered Furio showed a 310kg forward thrust at maximum power. With this thrust, takeoff run at 1,200kg (MTOW) to Vr is above 300m. Static performance tests from the CRPS-equipped vehicle showed 470kg forward thrust and, interestingly, 360kg reverse thrust. (The difference in forward and reverse thrust is due to the bias in propeller design to maintain maximum forward propulsive efficiency.)

The first two graphs above show that torque/yaw (orange curve), induced by the CRPS propellers running separately, increases with power and thrust (blue curve). This would cause an aircraft to yaw left or right depending on the direction of propeller rotation. The third graph shows that the torque, induced by the same two propellers running in contra rotation, is effectively zero at any power setting. The aircraft would therefore experience no yaw.

The test program revealed many other important characteristics of the CRPS design. No initial warming cycle was required prior to operating the power/thrust level to maximum power or other →

TOP TO BOTTOM: **mechanical simplicity – the two splined collars (right in photo) bolt directly to the rotor inside each motor. The longer of the two shafts fits inside the short outer shaft, which has an integral propeller hub, to form the coaxial contra rotating assembly (the second propeller hub is not shown); CRPS drive unit, showing the front bearing support and coaxial shaft with twin propeller hubs; and a rear view of the same, showing the rear bearing support for the coaxial shaft assembly**

settings. No cooling or idling period was required to avoid shock cooling. Between tests the CPRS was simply turned off and on, and switched to forward or reverse as required. As a true 'twin engine' system each propeller could be operated independently through the control system and static and mobile tests were completed using single propellers to drive the test vehicle forward and in reverse to record single engine performance and simulate engine failures.

The CRPS unit runs vibration-free at all power settings. The unit was bolted directly to the test frame with no anti-vibration mountings or provisions. There are no exhaust emissions and very little heat output.

No maintenance or fluid level checks were required between tests. This is a function of the extreme simplicity of the design. There are only two rotating components (two shaft/propeller/drive ring assemblies) other than the bearing assemblies, which are sealed self-lubricating components. In addition there are two motor cooling pumps.

The motors and motor cooling pumps are virtually silent at full power. Noise is limited to that from the propellers which was subjectively identified as lower than that emitted by a single, 'same power' propeller.

Next steps

CEP Ltd, has chosen a Falcomposite Furio aircraft as the best airframe to install and flight test the CRPS, as it is supplied in kit form. Built without any combustion engine components and instruments, the airframe can accommodate an 850kg payload (including occupants), sufficient to install the complete CRPS →

The test crew preparing for mobile runs on the runway at Gloucestershire Airport

ABOVE: **Falcomposite Furio with 180hp piston engine installed.**
BELOW: **CG image of the Furio with the planned 300hp electric CRPS. The elimination of 'swirl', deletion of radiator intakes and improved aerodynamic profile will elevate performance significantly. The aircraft would also qualify as a 'twin engine' type and have enhanced access to airspace over built-up areas etc**

ABOVE: **the CRPS fitted to the test frame complete with cooling system and instrumentation. The assembly weighs 88kg**

RIGHT: **the control box and data- gathering computer used to operate the CRPS system. For static tests the control box interfaced remotely with the vehicle through a 25m umbilical. During mobile tests the control box was operated from within the vehicle by the co-pilot**

equipment, power electronics and twin 200kg, 43kWhr battery packs, giving the aircraft up to a one hour flight time.

The elimination of the normal swirling propeller slipstream, loss of cooling air intakes and improved aerodynamic profile will elevate performance significantly. The aircraft would also qualify as a 'twin engine' aeroplane and have considerably enhanced access to controlled airspace.

To undertake the Furio project requires an investment of £450k. This level of funding is not presently available in CEP Ltd, and external finance is being sought. The company is therefore undertaking a development that is within its investment capability, that of an 'entry level' single-motor, geared, contra-rotating system. This system will provide yaw-free forward and reverse thrust, a continuous power of 125kW (155hp) and, importantly a maximum power for takeoff and climb of 250kW (310hp)—far greater than the present piston powerplant with which the Piper Super Cub floatplane is equipped. An Alaskan company has offered the aircraft stripped of all internal combusion engine components plus the engineering skills and facilities to install and flight test the equipment, at their cost.

A 65kWh battery pack and all power electronics operating at 600V DC will be delivered with the system. A single motor delivers power to a simple 1:1 ratio gearbox where the inner shaft of a coaxial pair passes straight through the gearbox to power the forward propeller and a set of gears and shafts take power from the central shaft and deliver it to an outer, hollow coaxial shaft to drive the rear propeller.

Power control will be a single proportional 'thrust lever'—forward for more power, backwards through a gate for reverse power. There are of course no mixture, manifold pressure or prop pitch controls. Reversing the motors in contra-rotation provides yaw-free thrust and facilitates extremely rapid deceleration on water, ice, snow and slippery surfaces and in emergencies.

Finally, electric CR has huge implications for the design of the next generation of military trainers. Present day single-engine turboprop military trainers simulate the experience of pure jet flight using complex computer driven actuators and trims to counteract yaw. An aircraft with electric CR propulsion would simply not need these systems.