ThinGap®
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BLDC DUCTED-FAN MOTOR FOR UNMANNED VEHICLES

A high-efficiency brushless *ring motor* developed by ThinGap Corporation of Ventura, California based on its patented electromotive coil technology promises to reduce energy consumption, allowing such small Unmanned Vehicles (UV), light enough to be carried by a man into reconnaissance or combat situations, as air (UAV), ground (UGV), underwater (UUV) to have plenty of operational time. For small UAV's this means enough operational time for surveillance, sensing and swarming. For UGV's and UUV's, the ring motor can eliminate transmissions; allow larger payloads, and the ability to move faster, farther or longer between battery charges.

In many UV applications, gas and diesel engines can be impractical due to noise and heat signature. Gas and diesel engine UV's create noise and generate heat, which can warn an enemy, eliminating the crucial strategic element of surprise. As a result, information and the crucial element of surprise can be lost. The problems extend beyond the noise, which sounds much like an RC-controlled airplane, to include vibration that weakens image quality and a heat signature that can be picked up by night vision devices. Gas and diesel engines can be silenced with heavy mufflers and special equipment, which affects payload and operational time; but does nothing to improve imaging quality or heat signature.

Electric motors have been under consideration for a while, but weight restrictions have limited the battery size, in turn limiting operational time. The most efficient battery that met weight limitations coupled with the most efficient motor had proved impractical because it required a transmission, which reduced efficiency by creating gear and generated additional heat. For example, a ducted-fan for UAV applications drained the battery of all the current just to get airborne, leaving no power for the flight or optical imaging equipment.

Ring Motor Technology

The unique brushless *ring motor*, designated the TG8250, developed by ThinGap Corporation under DARPA contract DAAH01-03-C-R080 is undergoing further development for a variety of UAV, UGV and UUV applications. The TG8250 ring motor delivers 1.5 HP (continuous) per pound, as well as provides a form fitting platform, which is quiet, cool running, conserves battery power and provides a gyroscopic effect that reduces vibration and stabilizes the UAV.

Ring Motor.

The ring motor looks like a steel ring with an outside diameter of approximately 8.25 inches, coupled to an iron, inner ring, with an inside diameter of 7.5 inches and height of 1.4". A copper centered ring forms the stator which sits inside the iron rings. In fact, it doesn't look like a motor with its large open inner diameter surrounded by the 0.374" thick ring that makes the motor. The shape of the ring motor is part of what makes it an ideal solution for ducted-fan, direct wheel and screw drive propulsion.

In ducted-fan applications, the blades fit within the inside diameter of the *ring motor* and the steel outer ring becomes the rotating member over which nacelles or composite structures can shield the mechanics of the outer ring. With a large diameter ring, the motor creates a gyroscopic effect stabilizing the craft similar to the rotors of a helicopter in flight. The stator and rotor's magnetic fields create a fixed path at the centerline of rotation. Offsetting the rotor magnetic field from its path within the stator magnetic field creates a magnetic force that resists the offset. This increases stability, allowing UAV's to fly during rough weather conditions; and for other types of UV's it damps vibration, improving imaging capabilities.

Understanding this unique technology requires a basic knowledge of conventional DC brushless motors. The typical DC brushless motor consists of a rotor and stator. The permanent magnets are mounted to the shaft and rotate, representing half of the magnetic circuit. The stator coil is stationary and made of copper wire wound around iron laminations or other material to support the windings. The other half of the magnetic circuit, the lamination stack is next to the coil and remains stationary. The ring motor is fundamentally different from a conventional DC brushless motor in two ways: the coil and rotating parts of the motor.

The TG8250 ring motor coil (stator) replaces wire windings with precision-machined copper sheets formed into a circular coil, allowing a higher copper-packing density than copper wire. The coil assembly is a free-standing coil structure without supporting laminations. By winding the coils in parallel or in series, the stator assembly can be operated at 50V to 280V or at three different torque constants. For example, at 72V, the motor operates at 75% efficiency, for motor and controller, with all 4x coils in series, and provides shaft output of 1,200 watts. With quadruple redundancy, if one coil fails, the motor continues to operate, allowing the mission to continue. Since iron is not used in the coil, the magnetic field does not affect inertia, reducing rotational losses, (eddy currents in the laminations) and allows the non-operating coil to freewheel, very much like auto-rotating helicopter blades.

The rotor consists of a U-shaped iron channel with a thin inner wall and magnets mounted to the inside of the outer steel ring. This structure forms a channel within the ring that accepts the stator coil. The entire magnetic circuit rotates, eliminating the iron losses typical of conventional brushless motors. The only remaining parasitic losses are the eddy current losses (AC losses), which exist in the coil, which is minimized by its design.

The rotor features 24 magnetic poles, providing higher dynamics. Essentially, the number of poles is a tradeoff between the AC losses in the conductors and the total weight of motor. The more poles in a particular design, the lighter the rotor can be due to the reduction of iron required for the magnetic circuit.

Different Applications

Customer-specified speed and torque requirements can be achieved by varying the winding configuration of the stator coils. For example, the TG8250 configurations of the four coils, one for each quadrant, were changed by using parallel and/or series wired circuits. The ability to reconfigure the coils allows the motor to be used in different applications. By making the coil and magnet dimensions longer, the torque per amp increases and the RPM per volt decreases proportionally, while HP output more than doubles. For example, torque and total horsepower output can be doubled by lengthening the motor 0.40 inch in the TG8250.

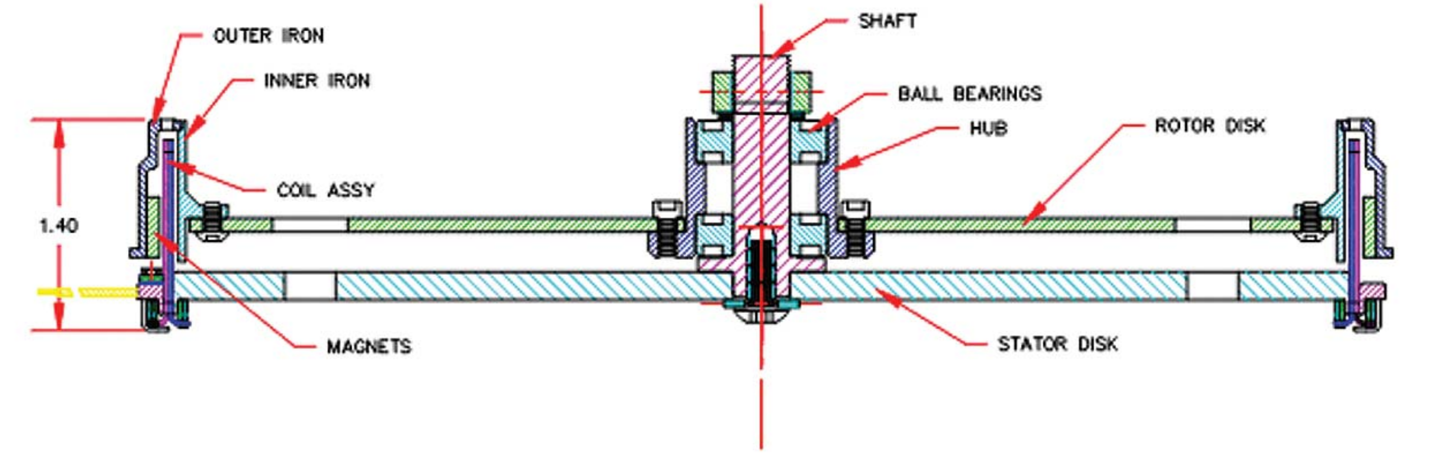
In UUV applications, the ring motor can be used as a counter-rotating underwater screw drive motor, providing direct drive for screw drive shafts at 2-4,000 RPM. The marine motor cooling system is very efficient at dissipating heat, which improves power output and battery life.

Under the latest Darpa contract (Contract No. W31P4Q04CR267) a larger version of the TG8250 is being developed: the TG14000. It will be 14” on the rotor Outside Diameter with a height of 5” and weight of 30lbs. The TG14000 will develop 6.5HP constant output from 500 rpm to 5600 rpm, matching the requirements of a UGV. The speed torque curve of the motor suggests that the optimized output will reach 40HP, or 30Kw output.

For UGV applications, the TG14000 ring motor will deliver enough peak and high torque at low speed to eliminate gearboxes and drive trains in smaller vehicles, although larger vehicles will use a gearbox. By eliminating the magnetic detent, the TG14000 will deliver very smooth and cogging-free rotation, even at slow speeds. Furthermore, the ring motor is envisioned to mount directly to the wheel, improving control and maneuverability.

Current Waveform

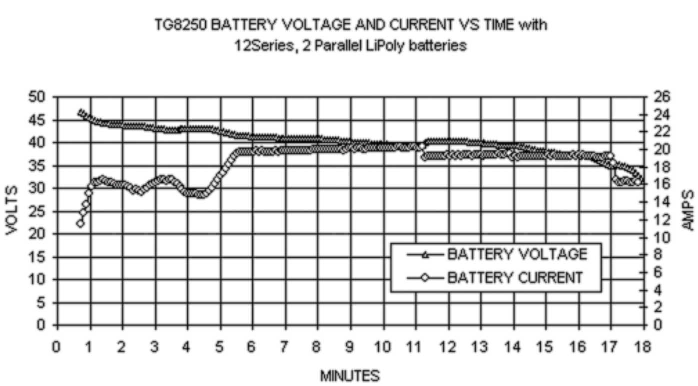
Traditional BLDC motor construction limits the speed a multi-pole iron core motor can reach because its phase waveform cannot switch fast enough at high speed. This is caused by the high inductance of the iron core. The very low inductance of ThinGap’s coil design allows high-frequency operation of the amplifiers (high-speed switching of the current). This allows the use of more magnets, which creates a higher pole count and reduces the iron mass to which the magnets are attached. In turn, this reduces the weight of the coil. With less weight and a higher pole count, the high speed characteristics of the motor have very few limitations. Basically, the current is switched on and off, depending on the location of the rotor, to create motion, torque and inertia. To match the operational speed of a motor with a ThinGap coil, the pole count of a traditional motor will have to be lower, increasing the weight.



Cross-section of the mating rotor ring assembly, consisting of a U-shaped iron channel with a thin wall and magnets mounted to the inside of the outer steel ring.

Battery Operation

Enough battery current must be available for the UV to complete its objective and still have a reserve. UV's in general and UAV's in particular have weight limitations, affecting the size and weight of the battery, which limits capacity. In some applications, battery packs are being designed for recharging with portable generator systems carried on HMMWVs for multiple operations. Typically, there isn't time to recharge a UV during a combat or reconnaissance operation.



The graph shows time of operation to be approximately 17 minutes. The temperature rise of the rotor was negligible and the stator temperature rise was 29 degrees C.

The ring motor has been tested with an 80V lithium-polymer battery pack as a power source. A dynamometer with a power analyzer was used to measure input power to measured output power of the motor. The power consumed by windage (air or water resistance) is not measured by dynamometer testing because it is not converted to shaft power. For example, a propeller would sustain drag losses, such as in screw or ducted-fan applications.

The test results proved the batteries could supply approximately 17-minutes of power before degrading, which is more than enough time for most live-situation intelligence situations. The temperature rise of the rotor was negligible and the temperature rise of the stator was 29° Celsius as bench tested without fan cooling. The lithium polymer battery pack showed strain from a continuous discharge rate of 2.8-C (three times capacity), (note: previous UAV's were operating at 5C+ during lift off) with one cell pack overheating during each test run. The temperature rise of the battery was about 25° Celsius. The temperature rise of the damaged batteries was 46° Celsius.

Roughness during the first few minutes of operation was attributed to the PID loop (Proportional-Integral-Derivative), which describes the compensation structure used in the dynamometer's closed-loop system. This was a minor operational issue that was tuned on the fly and can be addressed in production. The torque level was reduced slightly at the 11 minute and 17 minute marks.

Conclusion

The *ring motor* design is extensible with simple length increases of the coil and magnet structure, i.e. 0.40in. / HP. When the length of the motor is extended, the geometric design of the coil design makes the conductors self-compensating by gaining width as the motor is lengthened. Therefore motor resistance remains the same as the motor length and HP rating. With the drive current similar in each size of motor, the I^2R losses (power lost in the resistance of the motor windings) remains the same as the HP output increases, resulting in higher efficiency as the motor power output increases. Achieving power output in the four to five HP range appears to be very reasonable and as the motor size increases performance is enhanced.

This TG8250 *ring motor* configuration is capable of producing the required 1-HP output level with a 7.5-inch inside diameter bore and more. The capability appears to be closer to 2+HP continuous operating range. Cooling in flight will potentially allow higher power levels to be obtained. The high efficiency performance of the TG8250 allows battery operation. The low heat gain, a secondary benefit of the low-loss design, allows intermittent (such as battery powered) performance at a high-energy conversion level and high power input. The efficiency of the motor remains high over a wide performance range.

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