

Disruptive Advance in P.M. Motor Technology Provides Higher Top Speed and Extended Range

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ABSTRACT

The electric vertical takeoff and landing (eVTOL) industry can benefit from a disruptive advance in permanent-magnet motor technology that increases top speed and extends range. The Dura-Trac Motors field-weakening technology is mechanical, fail safe and well proven in the commercial-vehicle hybrid industry for 15 years. This technology is being introduced to the eVTOL market. The technology can be part of a ground-up design motor or added to existing brushless motor designs as a motor-manufacturer option, requiring few modifications.

DuraTrac mechanical field-weakening technology is far superior to electronic field-weakening for achieving higher motor speeds. During cruise flight, DuraTrac acts as a transmission, enabling motor top speed to be increased up to 40% on command. Because DuraTrac technology preserves high motor efficiency, range is also extended. The Dura-Trac technology allows greater flexibility for the user to select greater speed and range to suit the mission while continuing to provide the high torque required for hover and lift performance.

INTRODUCTION

The advance of multi-rotor drones and work by NASA and others in distributed electric propulsion has spurred the expanding capabilities of eVTOL craft. These advancements focus on multiple electric-lift motors with simple fixed-pitch props and redundant fault-tolerant controls. Brushless permanent-magnet (PM) electric motors provide a power dense, light weight and fault tolerant propulsion method. Nonetheless, further advancement in motors and controls is needed to optimize performance, range and efficiency with existing and future battery and energy storage technologies.

This paper introduces a method that is applicable to all brushless PM motors by extending the dynamic speed range beyond the normal limits without sacrificing efficiency. DuraTrac field weakening provides the advantages of a transmission or an adjustable-pitch propeller without the complexity of these alternatives.

RISE OF EVTOL AIRCRAFT

In the past eight years, we have seen the convergence of electric motor, battery, GPS and electronic control technologies to enable the rapid growth of the drone market. This development of quad, hex and octo drones using redundant high-output brushless PM and simple fixed-pitch props has formed the justification for distributed electric propulsion (DEP).

Early proponents of DEP have been Dr. Mark Moore of NASA, JoeBen Bevirt of Joby Aviation and others. The

NASA X-57 research plane used (18) electric motors to energize wing lift in the LEAPTech Project. (Ref.1) (Ref. 2) The use of (4) or more brushless PM motors with a simple fixed-pitch prop provides distributed propulsion, simplicity, and redundancy for the rapid expansion of eVTOL designs emerging during the last few years.

Kenneth I. Swartz summarized this expansive growth of eVTOL craft in his article “Charging Forward – New eVTOL Concepts Advance.” (Ref. 3) This excellent article chronicled the Uber Elevate Summit 2017 with over 500 stakeholders in attendance.

UNDERSTANDING THE ELECTRIC MOTOR – THEY’RE NOT ALL THE SAME

We are surrounded with an increasing number of highly efficient motors that use both permanent magnets and electric commutation – commonly called brushless PM motors. These designs can have the magnetic rotor on the inside of the coils (internal rotor) or on the outside of the coils (external rotor or outrunner). External-rotor designs are favored as spindle motors for your hard-disk drive and computer cooling fan due to their higher torque for a given size. External rotor PM motors are often a popular choice for drone and eVTOL lift motors.

Understanding the operating characteristics of PM brushless motors can improve our applications in the eVTOL field. For example, the same rules apply to internal and external rotor PM motors. The performance of these motors is generally

very linear, which helps us understand, estimate and compare performance.

For a given motor design, motor speed (RPM) is linearly proportional to voltage. With increasing load (torque), the speed curve usually has a constant slope. Output torque is linearly proportional to the current (Amps) and the current curve usually maintains a constant slope. This produces a characteristic graph that is shown in Fig. 1. Note that for a given torque, you can read the speed on the solid line and amps on the dashed line. Compared to other electric motor types, these curves in a brushless PM motor are amazingly linear and constant slope. This makes predicting PM motor performance much easier. For a more detailed explanation, see (Ref. 4).

The key motor/prop performance specification for eVTOL applications is vertical lift thrust. Lift thrust is often set at 125%-150% of the static hover thrust required to enable vertical acceleration and to allow a margin for high-altitude and/or high-temperature conditions causing reduced performance. This lift thrust point is often near the maximum power or maximum efficiency points on the motor curve or the motor is oversized for the application.

What Brushless Motors Can/Cannot Do

Brushless motors that utilize the new high-energy rare-earth magnets have especially high torque and power outputs for their weight. This makes these magnets well suited for eVTOL and drone service. One characteristic of permanent-magnet motors that can limit performance is a narrow dynamic-speed range. Because the strong permanent magnets create their own field, at increasing motor rpm the magnets induce an increasing voltage in the stator coils, called the "Back Electromotive Force," or Back EMF.

When this back EMF builds up to the level of the supply voltage of the batteries, then increases in motor rpm hit a wall and the motor is at maximum rpm. With the high torque, lower-speed motors suited to eVTOL and prop-drive applications, this means that when a motor is unloaded by factors like aerodynamic lift of the vehicle in cruise, the increase in rpm is modest at best.

This paper illustrates how the brushless motor rpm performance can be extended by using a mechanical field-weakening technique that achieves significantly extended cruise speed and range while preserving high efficiency. Mechanical field weakening acts like a transmission or torque converter,

but it is a light and fail-safe option that can be added to existing motor designs (Ref. 4).

Configuration of a Typical eVTOL Air Vehicle

The Surefly eVTOL air vehicle, a product of Workhorse Group, Inc., is representative of an (8) electric motor vehicle where lift motors provide both lift and forward thrust. When the eVTOL vehicle transitions from vertical hover to cruise mode, the horizontal centerline is tilted to provide forward thrust just as a helicopter does. Increasing forward speed generates aerodynamic lift and lift reduces required thrust to maintain level flight. As we see in Fig. 1 of a typical PM performance curve, reduced torque allows only a modest increase in motor and prop speed. This is due to the narrow dynamic speed range of the high torque/lower speed motor.

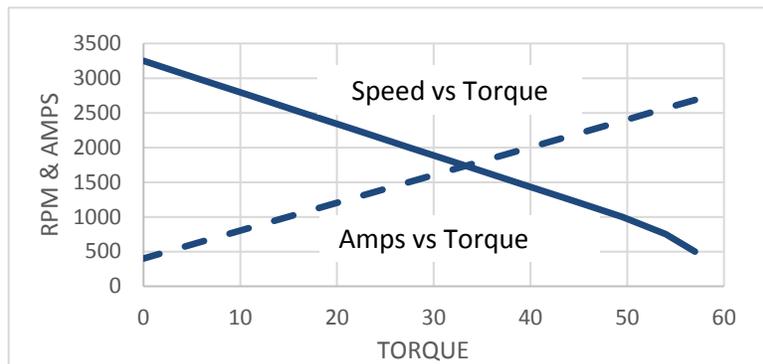


Fig. 1 – Typical relationship between speed, torque and amps in a brushless PM motor

How Does the PM Motor Work in an eVTOL Application? Surefly as an Example.

In the Surefly vehicle by Workhorse Group (Fig 2), maximum cruise speed is listed as 75 mph (121 km/hr) using the motor/prop technology available. Even though the body and arm shape may generate significant amounts of aerodynamic lift at cruise, the back EMF and characteristic PM motor curve restrict the motor-rpm dynamic-speed range. If a transmission could be added between the motor and the prop, motor rpm could be increased during cruise.



Fig. 2 – Surefly – Courtesy Workhorse Group, Inc.

Unfortunately, weight and complexity make this hard to justify. If a controllable pitch prop were available, then changes in prop pitch would extend the cruise speed range. The added complexity of controlling and synchronizing pitch of (8) props provides several additional failure modes to consider. Most eVTOL vehicles rely on the simplicity and redundancy of a fixed pitch prop that is directly driven by a brushless PM motor.

Field Weakening – Mechanical vs. Electronic

Dura-Trac technology can be added to an existing brushless-motor design or used in a new motor design. By weakening the magnetic effect between the rotor and stator coils on command, cruise speed can be extended by up to 40%. The mechanical field weakening effect acts like a transmission, but it is a simple and fail safe way to extend motor rpm that is inside the motor case. This mechanical method of field weakening preserves the motor high efficiency, unlike electronic field weakening methods. Electronic methods use additional energy to “buck” the rotor magnetic field, resulting in a major efficiency drop. Fig. 3 compares extended motor speed using Dura-Trac compared to electronic field-weakening methods (Ref. 5).

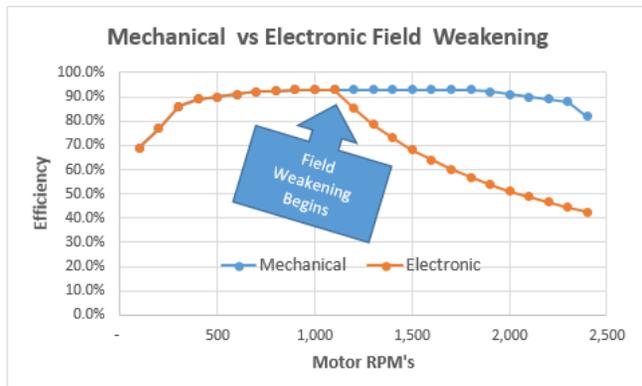


Fig. 3 – Efficiency difference between Mechanical and Electronic Field Weakening. Courtesy Duratracmotors.com

Does Dura-Trac Really Work?

Commercial shuttle buses and delivery trucks require very high launch torques due to their weight. For a commercial vehicle hybrid, a conventional brushless motor could produce this massive torque, but the top speed of the motor was limited to 10 mph (16 km/hr)! The application required a top speed of 35 mph (56 km/hr) for urban and suburban applications. The Dura-Trac motor achieved the required expanded speed range by applying field weakening to this motor.

The Dura-Trac hybrid accelerated the bus from a stop with full-launch torque. As speed approached 10 mph, the motor controller moved the magnet rotor to field weaken as needed, functioning as a magnetic transmission. During deceleration, the field weakening effect was reversed to optimize regen

braking of the brushless PM motor. In instrumented long-term testing, the Dura-Trac system increased shuttle bus miles per gallon (MPG) (L/km) by 25%. This hybrid system has been in successful operation since 2005. This technology was torture tested and Cummins Engine approved for heavy-duty commercial service. The eVTOL industry can gain similar performance advantages by adding this disruptive technology to existing or new motor designs.



Fig. 4 – Crosspoint Kinetics hybrid using Dura-Trac field weakening technology – Photo courtesy Crosspoint Kinetics

HOW TO IMPLEMENT DURA-TRAC FIELD WEAKENING IN EVTOL VEHICLES

Most eVTOL motor applications do not need the massive launch torque or wide dynamic speed range required by commercial vehicles. Field weakening, on a reduced scale, can provide a very beneficial increase in cruise speed and range in many eVTOL applications. (Ref. 6) The enabling factor in the eVTOL operating cycle is the benefit of generated aerodynamic lift due to body shape and increased cruise speed. Any lift generated can proportionally reduce motor torque required.

By incorporating limited magnetic field-weakening shift to a typical external rotor PM motor, the resulting rpm increase can enable significant increases in eVTOL cruise speed and range performance. Let’s look at how this disruptive PM brushless technology can be applied to a typical eVTOL craft.

Dura-Trac Field Weakening Application Example

Baseline performance of a two seat eVTOL vehicle using (8) conventional external rotor brushless motors with fixed pitch props is used as an example. This system enables hover and vertical climb capability for a maximum gross weight of 1,800 lbs. (816 kg). In cruise mode, the fixed motors achieve a cruise speed of 75 mph (121 km/hr).

If the body and strut profile is optimized for aerodynamic lift generation, then 20-30% generated lift may be achieved at 75 mph (121 km/hr). With this additional lift reducing the required motor torque, partial magnet field weakening of the rotor can increase motor / prop rpm to achieve a higher cruise

speed. In this example motor, a 15% field weakening shift increases rpm by 17% and a 30% shift increases rpm by 40%. Fig. 5 shows the typical torque/speed/efficiency of this method.

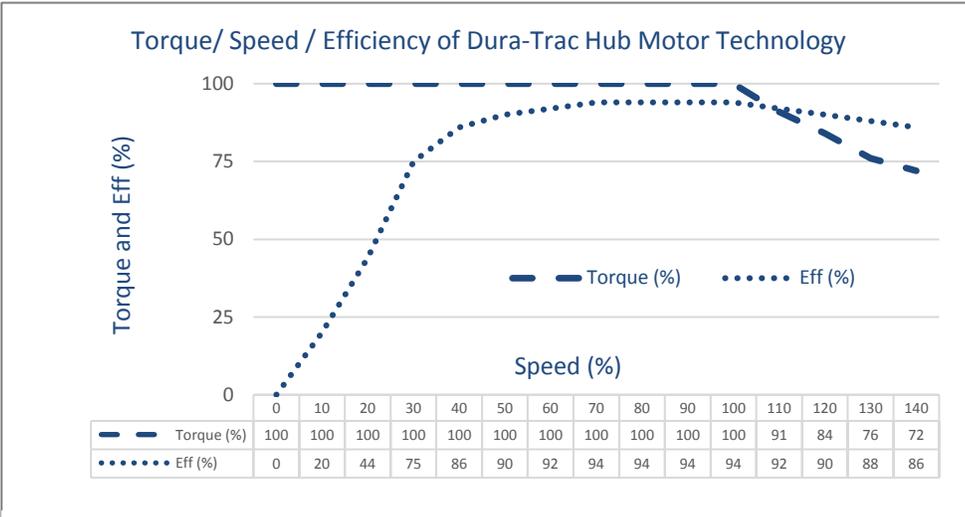


Fig. 5 – Typical torque/speed/efficiency using DuraTrac mechanical field weakening

This method enables important cruise-speed extension that can be added to existing motor designs. Because the majority of fully engaged motor efficiency is preserved by this small amount of magnet decoupling, this also enables important range extension benefits using existing energy storage technologies, as shown in Fig. 5. This method is superior to electronic field weakening, which drops efficiency significantly – creating a severe penalty for increased speed that spoils range, as shown in Fig. 3.

Adding Field Weakening Technology to a Typical Motor

A cross section of a typical external rotor (or out-runner) brushless motor for eVTOL is shown in Fig. 6. The domed rotor housing carries the high energy magnets on the inside diameter and this structure rotates on the shaft. The prop is bolted to the hub, allowing a simple and rugged connection. The motor stator contains the drive coils and is stationary and concentric inside the hub.

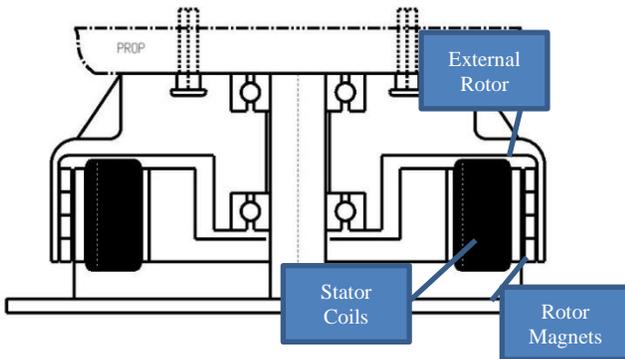


Fig. 6 – Cross section view of a typical external rotor PM motor for eVTOL applications

A cross section of a DuraTrac field weakening brushless motor for eVTOL is shown in Fig. 7. Note that in this fully engaged position, the rotor magnets and stator coils are common with the conventional motor, which makes conversion to a field weakening design much easier and more cost effective.

The motor performance is identical to the conventional motor shown in Fig. 6 and full-design torque and speed for hover is achieved. The domed rotor housing contains an internal hub with a splined connection to the motor shaft.

In this diagram, a ball spline connection is shown. The shaft rotates with the external rotor structure and contains a hub that is bolted to the prop. A shift actuator is located between the rotor hub and the stator coils. Several technologies are available to

provide the electrically controlled axial shift of the external rotor.

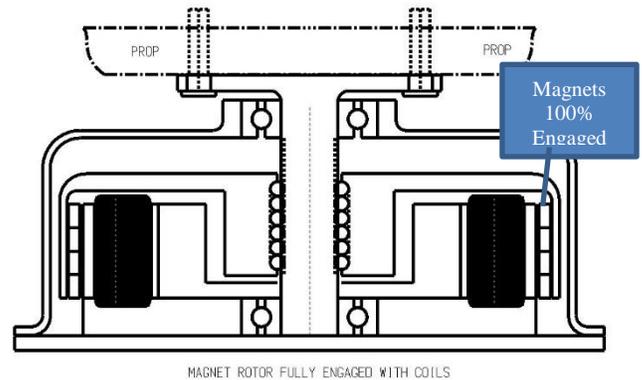


Fig. 7 - Cross section view of a typical DuraTrac PM motor with rotor magnets fully engaged with the stator coils

Effect of Dura-Trac on Flight Performance

When the air vehicle reaches cruise speed and aerodynamic lift is generated, a portion of the maximum design torque can be traded for additional motor rpm by the use of field weakening. In many eVTOL applications, two-position axial field-weakening may be sufficient for simple and reliable control of extended speed. (In other cases, multiple shift positions are available using variable shift actuator technology.)

In Fig. 8, the spinning external rotor has been extended 15% by the shift actuator. Now 85% of the magnets are active with the stator coils and back EMF is reduced. The motor now follows a higher speed/lower maximum torque performance curve that enables a typical 17% increase in motor rpm. If the

shift actuator is turned off or disabled, then the magnets automatically retract to the 100% engaged full torque position for hover.

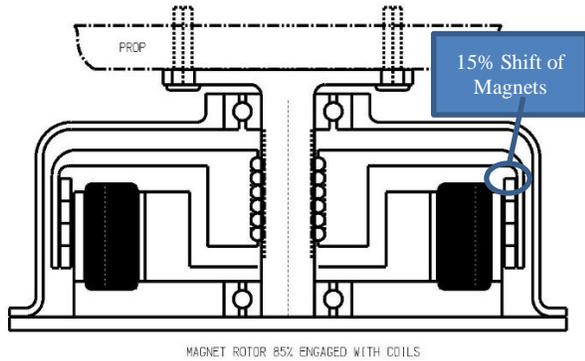


Fig. 8 – A typical DuraTrac PM motor with rotor magnets 85% engaged (15% shifted) with the stator coils to achieve a 17% rpm increase

If additional aerodynamic lift is generated, a greater portion of the maximum design torque can be traded to additional motor rpm by the use of field weakening. In Fig. 9, the spinning external rotor has been extended 30% by the shift actuator. Now 70% of the magnets are active with the stator coils and back EMF is reduced. The motor now follows a higher speed/lower maximum-torque performance curve that enables a typical 40% increase in motor rpm. If the shift actuator is turned off or disabled, then the magnets automatically retract to the 100% engaged full torque position for hover.

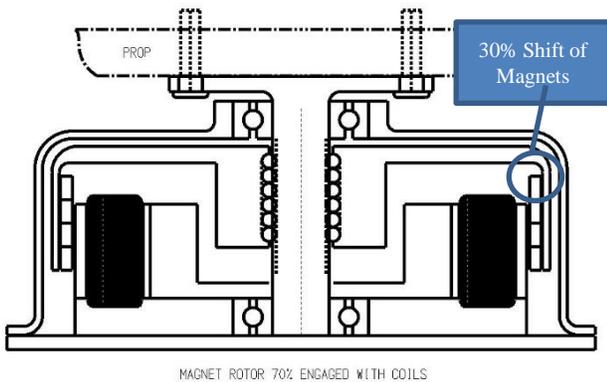


Fig. 9 – A typical DuraTrac PM motor with rotor magnets 70% engaged (30% shifted) with the stator coils to achieve a 40% rpm increase

The Physics (and Math) of Field Weakening a PM Motor

For a detailed discussion of the physics of both DuraTrac mechanical field weakening and electronic field weakening, see the white paper on the web site (Ref. 5). Have just a little time for some math? The following paragraphs explain the physics behind calculating the efficiency and torque of permanent magnet motors. Take time to read and understand. We promise there's no test.

As illustrated in Fig. 1 and Fig. 5, permanent magnet motors are linear with respect to their torque/speed performance and the ratio changes created by field weakening. While the following example is for just one motor configuration, the data indicate how mechanical field weakening can be applied to any PM brushless motor design.

$$\text{Extended speed} = (1 \div \text{decimal engagement}) \times \text{Base Speed}$$

- 100% rotor engagement, max speed 1,310 rpm's, at 96 V.
- 75% rotor engagement (25% decoupling) the speed increases to 1,746 rpm's. In this condition, 75% of the rotor is exposed to the stator coils (DuraTrac) or the magnets are bucked to reduce their attraction to 75% (Electronic methods). Because of the linearity of PM motors, this new maximum speed at 75% will be speed at 100% multiplied by $1 \div \text{the decimal engagement}$ $1 \div 0.75 = 1.33 \times 1,310 = 1,746$ max rpm's. The 1,746 rpm maximum agrees well with the dyno data for 75% rotor engagement.
- 50% rotor engagement (50% decoupling) the speed increases to 2,620 rpm's. In this condition, 50% of the rotor is exposed to the stator coils (DuraTrac) or the magnets are bucked to reduce their attraction to 50% (Electronic methods). Using the same method as above, we calculate: $1 \div 0.50 = 2.00 \times 1,310 = 2,620$ max rpm's. The 2,620 maximum agrees well with the dyno data for 50% rotor engagement.

If the original fully engaged motor torque is referenced from dyno data or a published performance curve, torque estimation is even easier. Multiply the fully engaged torque by the percentage of rotor engagement to get an estimate of resulting torque at the extended speed.

Adding Field Weakening Tech to Existing PM Motors

Existing motor designs used in the eVTOL field have a significant advantage when DuraTrac mechanical field weakening technology is added. The motor is already designed with appropriate performance for direct drive of the prop; weight, size and efficiency factors also have been optimized. The two most expensive sub-assemblies of the motor can be used with little or no modification: (i) laminated stator with wound coils; (ii) high-energy magnets. The stack length and air gap between the rotor and stator can remain the same.

Because many eVTOL applications require only a small percentage of shift, length change is small (Ref. 6). A rotor hub and shaft with a splined connection and an actuator does need to be added with one longer end bell for the axial stroke required. In many applications, a simplified two position actuator may be used that is electrically actuated from the motor controller. These features make testing the DuraTrac mechanical field weakening much easier and quicker, because many existing components can be applied.

Reliability, Efficiency and Dangers of Electronic Field Weakening

More than 20 years of reliability and efficiency history of on-road electric vehicles using electronic field weakening with PM motors can be applied to similar conditions in the eVTOL market. A DuraTrac white paper discusses the methods and impacts of additional energy used to buck the PM rotor magnets to simulate field weakening for extended speed (Ref. 5). Very few references reveal the high input of current needed and the major drop in motor efficiency when these currents are taken into account. The axial decoupling used by the DuraTrac system removes a portion of the magnets from the proximity of the stator, preserving high efficiency (Fig. 3).

The other danger presented by electronic field weakening is that the system is not fail safe if a controller malfunction occurs. Several on-road electric vehicles using electronic field weakening have experienced sudden motor-drive failures when the motor was operating beyond the normal maximum speed and using electronic field weakening.

When electronic-bucking field collapses, a large voltage spike can be generated, potentially failing the entire system. If a single motor controller shuts down in an eVTOL due to software, overheat or other conditions, a sudden dynamic braking of the motor causing a voltage surge can fail ALL motor-drive circuitry without rigorous voltage-spike safeguards. With typical interconnected battery packs, motor-controller power supplies and control circuits, electronic field weakening presents a serious risk to air vehicle safety and reliability.

CONCLUSIONS

- 1) The eVTOL industry can benefit from Dura-Trac Motors disruptive technology of PM motor axial field weakening to extend speed and range during cruise by 20-40%.
- 2) Aerodynamic lift generated during cruise can enable extension of the PM motor top speed through mechanical field weakening without the negative effects of electronic field weakening.
- 3) Many eVTOL PM motor applications require only a 15%-30% field weakening for performance enhancement, while retaining compact size of the PM motors.
- 4) DuraTrac field weakening technology can be added to existing motor designs, retaining many of the high cost components like the stator assembly and high strength magnets.
- 5) This technology was torture tested and Cummins Engine approved for heavy-duty bus commercial service. The eVTOL industry can gain similar performance advantages by adding this disruptive technology to existing or new motor designs.
- 6) DuraTrac mechanical field weakening retains high-motor efficiency and is fail safe, reliable and robust, unlike methods of electronic PM motor field weakening to extend rpm.

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