BEYOND CLEAN SKY: CARTERCOPTER SLOWED ROTOR / COMPOUND EXCEEDS EFFICIENCY AND EMISSION GOALS

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Abstract

Carter Aviation has its footing in environmental efforts with roots in the wind industry. Leveraging its very lightweight high inertia wind turbine blades for application as a rotor blade, Carter has developed its Slowed Rotor/Compound (SR/C™) technology as an alternative to conventional vertical lift. The benefits of slowing a rotor in cruise flight from both a drag and acoustic perspective are well understood, but doing so safely is another matter. Carter overcame 10 challenges to make the SR/C aircraft a reality, and with it, a new era of aviation is now possible. Runway independent aircraft (to include full hovering configurations) that possess efficiencies more akin to fixed-wing aircraft promise to deliver a cleaner, greener, and safer VTOL capability that exceeds environmental goals of Clean Sky 2. CO_2 emission reductions of 80% for the jump takeoff CarterCopters have been demonstrated and a 66% reduction for a full hovering heavy twin is predicted. And, all of this is accomplished with 15-20 EPNdB less noise than helicopters.

1. NOTATION

A	= rotor disc swept area, ft²
C_D	= blade drag coefficient, dimensionless
CG	= center of gravity
HP_o	= profile horsepower
D	= drag, lbs
dh	= vertical velocity, ft/s
L	= lift, lbs
P_{drag}	= power produced by drag, ft-lb/s
$P_{propeller}$	= power produced by propeller, ft-lb/s
P_{ROC}	= power associated with climb/sink, ft-lb/s
ROC	= rate of climb, ft/min or ft/s
T	= thrust, lbs
TAS	= true airspeed, mph or ktas
V	= freestream velocity, ft/s
W	= weight, lbs
µ	= advance ratio, V/(ΩR), dimensionless
ρ	= freestream density, slug/ft³
$ρ_o$	= sea level density, slug/ft³
σ	= solidity, dimensionless
ΩR	= rotor tip speed, ft/s

2. INTRODUCTION

Nations around the globe have been addressing air quality and other environmental issues for decades. Encompassing similar goals in general, but with different foci, methods, and resources as well as different senses of urgency, these efforts have been more piecemeal than a fully integrated campaign to improve the environment. Addressing the aviation and aerospace industrial segment, the Clean Sky JTI (Joint Technology Initiative) was founded in 2008 as a totally integrated program to improve aviation fuel efficiency (reduce carbon emissions) as well as reduce noise pollution. The European Commission, in partnership with key European industry participants, formed the initiative and, with progress demonstrated, has furthered the program to cover the 2014-2024 timeframe under Clean Sky 2.

Among the Clean Sky 2 goals are fuel efficiency improvements resulting in a 20%-30% reduction in carbon emissions (CO_2) as well as a 20%-30% reduction in noise emissions (2014 technology baseline). The Clean Sky 2 goals are being addressed on multiple levels to include materials and processes, subsystem design and configuration with particular emphasis on propulsion, as well as airframe elements, and ultimately an integrated platform configuration. Funding is robust at a combined €4 billion between the European Union and industrial partners (cleansky.eu [1]). In a completely separate effort, a small aerospace company located in Wichita Falls, Texas has been diligently working to perfect an environmentally friendly vertical takeoff and landing (VTOL) aircraft.

The importance of vertical-lift to the world is well established. From the more mundane air taxi operations in congested environments to emergency medical services, search and rescue, and humanitarian relief missions, rotorcraft are recognized as a critical and lifesaving capability. Unfortunately and despite modern improvements, rotorcraft are notoriously inefficient, far exceed fixed-wing aircraft in per-seat-mile emissions, and have acoustic characteristics that are undesirable for flight over developed areas. Carter Aviation Technologies, LLC has been developing its Slowed Rotor/Compound (SR/C™) technology for over 20 years as an alternative to conventional vertical lift.

Carter Aviation has its footing in environmental efforts with roots in the wind industry. In the late '70s and early '80s, Carter Wind Systems developed the most efficient wind turbine of its time. The key enabler was

the very lightweight high inertia wind turbine blades. This same core technology is a critical enabling element of Carter's Slowed-Rotor/Compound (SR/C™) technology. Jumpstarted by the success in the wind industry, Carter Aviation was founded in 1994 with the mission to develop breakthrough vertical-lift technology – technology aimed at providing the world's safest and most efficient and environmentally friendly runway independent aircraft ever conceived. Enter the CarterCopter (Figure 1).

Figure 1. CarterCopter Technology Demonstrator (CCTD)

The CarterCopter Technology Demonstrator (CCTD) flew from 1998-2005 with many firsts. Most notably, the CCTD was the first aircraft in history to reach μ-1 (μ is the rotor tip advance ratio, and μ-1 is when the tip speed of the rotor is equal to the forward speed of the aircraft). The previous high of 0.92 was established around 50 years earlier by the McDonnell XV-1 (Harris [2]). The historic μ-1 flight of the CCTD took place on June 17, 2005. The aircraft also demonstrated high cruise efficiencies with an L/D of 7 at 148 kts, 1.5x that of conventional helicopters.

Figure 2. Second Generation CarterCopter – 4-place PAV

Today, Carter is flying their second generation SR/C aircraft, referred to as the PAV (Personal Air Vehicle – Figure 2). The PAV is a 4-place aircraft with a 45' rotor diameter and wingspan that is powered by a 350 HP turbocharged Lycoming IO-540 engine. The vehicle has demonstrated an L/D 3x better than today's helicopters, with efficiency expected to improve with

further testing. Examining a representative sample of today's light single helicopters, the average fuel burn is 2.4 lbs/nm. The PAV has already demonstrated fuel burn below 0.5 lbs/nm, and Carter anticipates achieving cruise efficiencies as good as 0.4 lbs/nm.

Converting the PAV's fuel efficiency to pounds of CO_2 emitted per nautical mile results in 1.58 lbs/nm. For the representative sample of conventional light single helicopters, the average carbon emission is 7.85 lbs/nm. This improvement in fuel efficiency and corresponding reduction in CO_2 emissions is plotted in Figure 3. As can be seen, the CarterCopter achieves a reduction in CO_2 of 80% over today's representative light single helicopters, and a reduction of 50% over the Clean Sky 2 goal. Noise reductions are nearly as impressive.
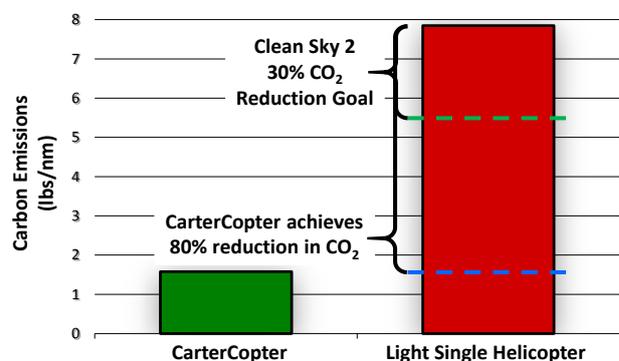

Figure 3. CarterCopter CO_2 emissions per nautical mile versus Helicopters

Flight at high advance ratios is key to the performance of CarterCopters. At μ-1, when the rotor is turning very slowly, the rotor rotational drag all but disappears, and with very long small wings, the aircraft efficiency is better than most general aviation aircraft and about 4 times better than typical helicopters. By being able to safely slow the rotor in flight, the technology allows for forward speeds in excess of 400 kts without the tip speed of the advancing blade going over Mach 0.9 (a well-established design limit). This is comparable to the cruise speed of some business jets.

Two of the largest contributors to helicopter flyover noise emanate from the main rotor and tail rotor, and the rotational speeds of these rotors directly contributes to acoustic energy. The CarterCopter has no tail rotor so that noise source is eliminated entirely. With the main rotor slowed from a takeoff rpm of near 400 to a cruise rpm as low as 100 rpm, the CarterCopter has very little rotor noise as well. Some of today's quietest helicopters have an effective perceived noise level (EPNdB) between 80-85 EPNdB for a 492 foot flyover cruise condition. The CarterCopter at the same condition is 15-20 EPNdB less than helicopters, representing the Clean Sky 2 goal of a 20%-30% reduction in noise.

Flight test data has proven that this technology can reduce fuel consumption and related emissions. The U.S. Army Aviation Applied Technology Directorate completed an independent review of Carter's flight test data, validating the data reduction methodology (Cox [3]). Beyond environmentally friendly efficiencies, the technology offers speed, range, reduced acoustic signatures, and safety that are unparalleled even when compared to the newest emerging technologies and configurations being developed in the rotorcraft industry across the globe. The remainder of this paper describes the fundamentals of SR/C technology, flight test data validation of performance, and implications for future vertical-lift aircraft design of both hovering and non-hovering CarterCopters promising cleaner, greener, and safer operations with a vehicle that delivers significantly reduced direct operating costs.

3. SR/C FUNDAMENTALS

As implied by the name, the key technology under-pinning CarterCopters is the ability to slow the rotor in cruise flight without requiring an infinitely variable speed transmission. Such a transmission represents a long desired capability for rotorcraft, as the benefits of slowing rotors have been understood for over half a century. One of the primary benefits is the remarkable drag reduction that slowing the rotor provides, which translates directly to reduced horsepower. As discussed in Carter & Lewis [4], rotor profile horsepower can be defined per Foster [5] as follows:

$$HP_o = \frac{\frac{\rho_o}{8} \sigma C_D A (\Omega R)^3 (1 + 4.6\mu^2) \frac{\rho}{\rho_o}}{550}$$

This can be separated into a drag due to rotation and a drag due to forward speed, with the rotational component being calculated by setting μ=0. Although this formula breaks down at very low rpms, it still illustrates the trend of drag vs. rpm as shown in Figure 4. With the rotational component being a function of RPM³, slowing the rotor has a very large effect on rotational drag. For example, if rotor supported flight requires 300 rpm, and the rotor can be slowed to 100 rpm in cruise (these are the rpm values seen in flight testing the PAV), this 3-fold reduction in rotor rpm corresponds to a 27-fold reduction in rotational drag, and a 5.5-fold reduction in total rotor profile drag.

Achieving a variable speed transmission that would allow this rpm reduction has been elusive for the industry, with significant challenges in complexity, weight, and installed volume. Some success has been had with multi-speed transmissions, but these efforts have achieved only modest reductions in rotor RPM with correspondingly modest improvements in efficiency. CarterCopters essentially emulate an infinitely variable speed transmission, but do so without a transmission engaged – CarterCopter rotors

autorotate in cruise flight, allowing the rotor rpm to be controlled independently of engine rpm.
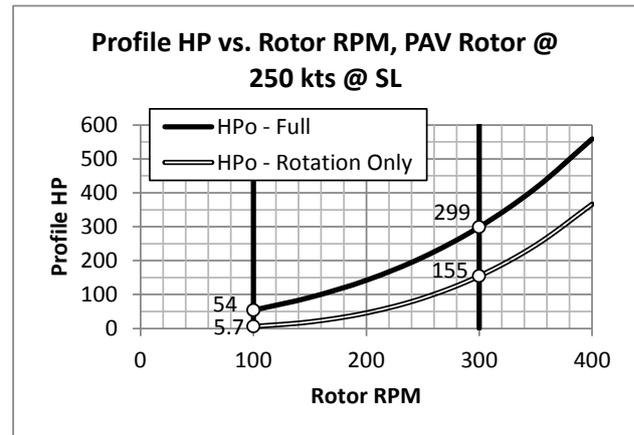

Figure 4. Rotor Profile Drag Reduction with RPM

4. SR/C CHALLENGES

Developing an autorotating rotor and related control system that permits flight at high advance ratios, while maintaining rotor stability in cruise flight, proved difficult with significant technical hurdles. It was these hurdles that led to the abandonment of SR/C research in the '50s and '60s. Carter faced this challenge, overcoming ten key hurdles to enable this capability. As described in Lewis et al [6], many of these issues were studied using both a blade element analysis developed by Carter and with the X-Plane flight simulator, and the strategies developed by Carter were successfully demonstrated in flight with both the CCTD and PAV aircraft.

4.1 Flapping/excessive coning due to lift with low centrifugal force on the advancing blade at high forward speeds (μ >0.6 to~5)

Analysis performed by Carter predicts a worst case ½ per rev flapping/coning instability when the advancing blade is at a 45° azimuth (1:30 o'clock), which was observed testing a 6 ft diameter rotor. This divergence can be controlled at least three ways: 1) increased mass in the blade tips for adequate centrifugal force, 2) a high degree of pitch cone coupling, and 3) a stiff blade and flapping lock-out mechanism.

Carter SR/C aircraft address this issue with a combination of high tip mass (see Figure 5) and pitch cone coupling. While previous concepts, such as the XV-1, have used stiff rotors, the increased structural weight for that approach tends to be heavier than adding mass to the blade tips. The pitch cone coupling, in addition to accommodating vertical gusts like in a conventional rotorcraft, also decreases flapping for advance ratios greater than 0.8. Increased lift will increase flapping and coning, which due to the pitch cone coupling will also reduce the blade pitch. On the advancing blade,
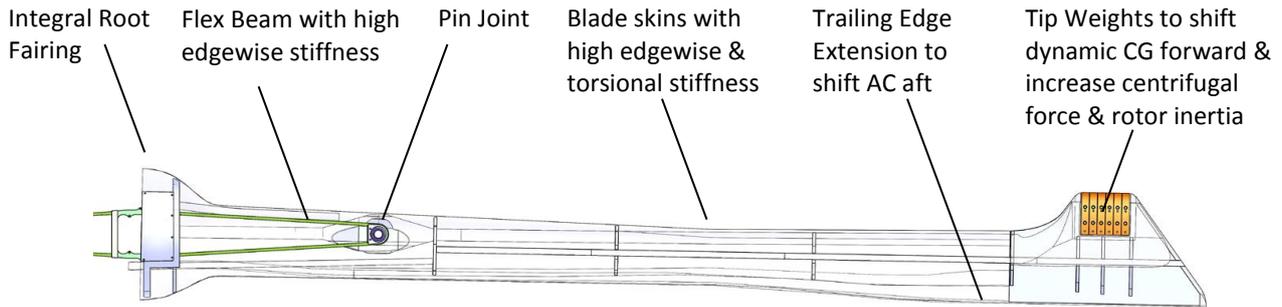
Integral Root Fairing

Flex Beam with high edgewise stiffness

Pin Joint

Blade skins with high edgewise & torsional stiffness

Trailing Edge Extension to shift AC aft

Tip Weights to shift dynamic CG forward & increase centrifugal force & rotor inertia

Figure 5. 45' Diameter High μ Rotor Flight Tested on PAV Prototype

this reduces the lift. On the retreating blade, because most airflow is reversed, flowing from what would normally be the trailing edge to the leading edge, this pitch change actually increases the angle of attack, causing the retreating blade to create more lift, reducing the flapping.

4.2 Flapping due to unbalance in lift between the advancing and retreating blade at high-μ (>0.6 to ~5)

Flapping balances the lift moment between the advancing and retreating blades by introducing a vertical velocity component to change the angle of attack, decreasing the angle of attack on the advancing blade and increasing the angle of attack on the retreating blade. This angle of attack change occurs whether the flow is normal or reversed. The worst condition for flapping occurs at μ=0.75, because this is the advance ratio where the retreating blade has the lowest average airspeed and the least capacity to produce lift – above μ=0.75 the increased reverse flow will increase the average airspeed, giving the retreating blade the capacity for increased lift.

Carter developed a simple, single means to control flapping at all advance ratios by controlling collective pitch, which is explained in detail in the Carter & Lewis patent [7]. Higher pitches will cause the rotor to create more lift and lead to higher flapping, while lower pitches will reduce the lift and lead to less flapping. While the normal cruise collective pitch of 0° should accommodate 50 ft/s vertical gusts, the ability to go to a negative collective offers even more ability to control excessive flapping.

4.3 Blade flutter/divergence on retreating blade

The retreating blade is prone to flutter instability due to the large portion of reverse flow. The local aerodynamic center of a region of the blade will be located at approximately the quarter chord, but based on the direction of airflow. In other words, in a region with reverse flow, the aerodynamic center will be closer to what would normally be the trailing edge, or at the three-quarter chord when measured from what would conventionally be the leading edge (Figure 6). Because the region of reverse airflow increases as advance ratio increases, the aerodynamic center of the

retreating blade will shift towards what would normally be the trailing edge. Once the aerodynamic center has shifted far enough, it will be ahead of the blade dynamic center of gravity (ahead as measured by freestream velocity), and the blade will become unstable about the pitch change axis.
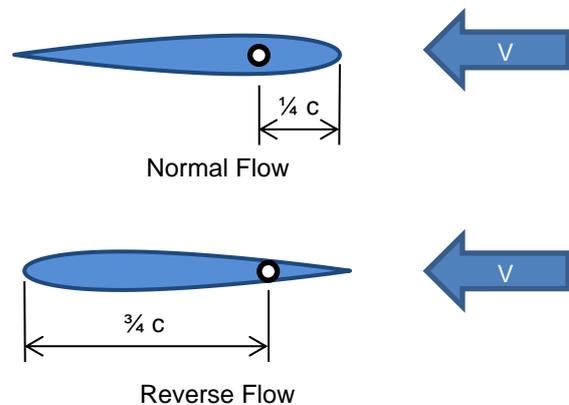

Figure 6. Aerodynamic Center Shift with Reverse Flow

Carter determined that with sufficiently torsionally stiff blades and a related stiff control system to transfer pitching moments from one blade to the other, the instability on the retreating blade can be countered by the stability on the advancing blade. If a disturbance created a pitching moment that tried to increase the angle of attack of the retreating blade, that same disturbance would create a pitching moment that tried to decrease the angle of attack on the advancing blade. If the pitching moment on the advancing blade is greater than that on the retreating blade, and the structure is stiff enough to transfer the moments between the blades, then the overall system will remain stable.

The above effect can be taken advantage of by increasing the distance between the dynamic CG and the aerodynamic center. Because the advancing blade has a higher relative velocity, this increased distance will increase the stability of the advancing blade more than the corresponding decrease in stability of the retreating blade, allowing the rotor to remain stable to higher advance ratios. There will be some advance

ratio where the reverse flow dominates and the rotor becomes unstable, which is dependent on the specific rotor geometry, and which is around μ=1.4 for the current PAV rotor. To fly beyond this advance ratio, boosted controls will be required, as is currently the case with most helicopters (note that Carter's 4300 lb PAV flies without boosted controls).

4.4 Rotor diving force sensitivity at high speeds where the rotor is mostly unloaded – the rotor plane of rotation less than 5º off air-stream

In an SR/C aircraft in cruise flight, the rotor is unloaded and lift is transferred to the wings, allowing the rotor to be slowed for the drag benefits discussed in Section 3. To do this, the rotor is disconnected from the engine and driven by autorotation. The rotor rpm is controlled by controlling the angle of the rotor plane relative to the incoming airstream. Larger angles allow more air to pass through the rotor, driving it to a higher rpm, while lower angles limit the air through the rotor, reducing the rpm. This angle is controlled by some manner of trim actuator, not cyclic stick input, since the rotor angle for rpm control must be controlled independently of maneuvering control inputs. In most Carter designs, this trim actuator has been a tilting mast, which offers additional benefits (see Section 4.6).

In the cruise condition, when the rotor is mostly unloaded and spinning at its lowest rpm, this angle is very small, meaning that even a small change in aircraft angle of attack is a large percentage change to the rotor angle, which in turn means a large percentage change to the autorotation driving force. This driving force sensitivity issue is addressed primarily through high rotor inertia, stabilizing the rotor rpm through transient angle of attack fluctuations, and limiting the rate of rpm change during prolonged angle of attack variations, preventing runaway excursions and giving the rotor rpm controller enough time to correct the rotor angle.

4.5 Control response at slowed rotor RPM

An early concern was that reduced rotor rpm which leads to reduced rotor control response would also lead to inadequate aircraft maneuverability. However, the results of analysis show that although maneuverability is reduced, it is adequate to control the aircraft. In low speed flight regimes where the most maneuverability is required, the rotor rpm will necessarily be high, providing high maneuverability. Maneuverability suffers the most in cruise flight at high speeds and high altitudes. But as in fixed wing aircraft, under those conditions the wing is operating at near max lift for the best efficiency, so rapid control inputs are not desired as they could lead to wing stall. Figure 7 shows typical values of flapping and max roll rate for slow rpms at various airspeeds and altitudes. Although maneuverability is reduced at higher airspeeds and altitudes, it is still sufficient to control the aircraft. This

can also be addressed operationally, accelerating the rotor rpm when higher maneuverability is required, but which comes at the expense of increased drag.

Alt (ft)	TAS (kts)	Flapping @ 2g turn		Max Roll Rate @ 12° flapping	
		200 rpm	100 rpm	200 rpm	100 rpm
S.L.	172	-2.10°	-4.19°	54.5°/s	27.3°/s
10k	200	-2.44°	-4.88°	40.3°/s	20.1°/s
25k	257	-3.13°	-6.26°	24.5°/s	12.4°/s
40k	345	-4.28°	-8.56°	13.5°/s	6.76°/s

Figure 7. Rotor RPM vs. Flapping vs. Roll Rate vs. Turn Rate vs. Altitude

4.6 High aircraft angle of attack in low speed autorotation

When the rotor is in autorotation in low speed flight, the rotor angle relative to the incoming air must be high to allow enough air to flow through the rotor. If the mast were at a fixed angle, this would force the entire aircraft to be at a high angle of attack, which was one of the limitations identified in Carter's first prototype, the CCTD. For climbout, this high angle puts the wing in a stall, and can also cause separated flow on the fuselage, substantially increasing drag on the aircraft and hindering climb performance. For landing, this high angle reduces pilot visibility and increases the risk of a tail strike during the landing flare.

Carter developed a long tilting mast to allow the rotor disc angle to be controlled independently of the overall aircraft angle of attack, while maintaining the rotor lift vector through the aircraft CG for proper pitch trim (note that this movement is only a trim that moves slowly, and that cyclic input is still used to change the rotor angle rapidly for maneuvering). For low speed flight, this allows the rotor to be tilted aft while the aircraft maintains a reasonable angle of attack, so that the wing isn't stalled during climbout, and so that the pilots have good visibility for landing, with clearance for a large landing flare without the tail striking the ground.

A tilting mast offers additional benefits. By controlling the rotor angle, it can be used to control rotor rpm during cruise when the rotor is unloaded (see Section 4.4). Because it provides a large fore/aft translation of the rotor center of lift, it allows for a wide allowable CG range. And by mounting the mast to the aircraft with low spring rate restraints, it provides the rotor with some freedom of movement, allowing it to absorb oscillatory loads with its own inertia, isolating the airframe from those loads. This is particularly beneficial to isolate the 2 per rev drag oscillation during cruise, and is so significant that the pilot reported no rotor vibration at high advance ratios, while the g-meter in the cockpit recorded only 0 to 0.01 g (on a calm day).

4.7   Rotor operation over a wide RPM range

While helicopters only operate over a narrow rpm range in flight, SR/C aircraft must operate over a wide range, from the high rpm for takeoff and rotor supported flight to the slowed rpm for cruise.   The cruise rpm can be as low as ¼ the takeoff rpm for jump takeoff variants, or ⅓ the takeoff rpm for hovering variants.   This introduces a bigger challenge in avoiding resonance than in pure helicopters.

To avoid resonant frequencies, the rotor for SR/C aircraft is made to be very stiff in the edgewise direction, such that the first natural frequency in the edgewise direction is higher than any rpm at which the rotor will operate. This is accomplished by using an I-beam type flex beam, with the caps positioned far enough apart to provide the necessary stiffness (see Figure 5).   The rotor is much more flexible in the flatwise direction, but any natural frequencies in this direction are heavily dampened by the heavy weights in the tips of the rotor blades.

4.8   High hub drag normally associated with rotorcraft

Historically, the rotor hub contributes ¼ to ⅓ of the total drag for a rotorcraft.   To reduce this drag, Carter designed a compact rotor head using a tilting spindle/hub design (see Figure 8).   The collective is independent of the cyclic, allowing for the required high torsional stiffness between the blades as discussed in section 4.3. This also allows the root fairings integral to each blade to remain aligned at the flat pitch used in cruise, since cyclic change does not change their alignment.   The rotor (see Figure 5), uses a flex beam that that's very stiff in the edgewise direction, but flexible torsionally and in the flat-wise direction to accommodate pitch change and coning, eliminating the hinges and bearings associated with a traditional rotor. This combination of features provides for a compact, streamlined rotor hub with much less drag than a traditional rotorcraft hub.
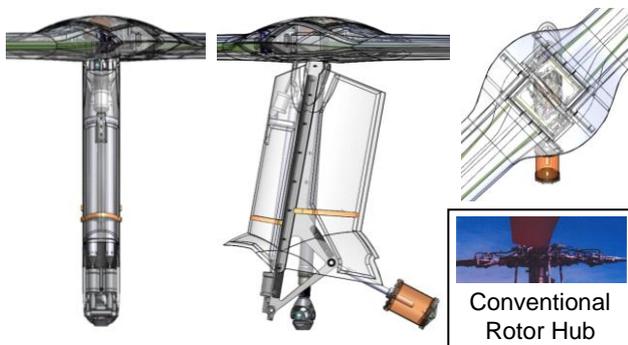

Conventional Rotor Hub

Figure 8. Streamlined Rotor Hub & Mast

4.9   Simplified, intuitive control between rotor and aircraft modes

To reduce complexity for the pilot, a simple, intuitive control interface is required that seamlessly blends rotor and aircraft modes of operation. SR/C aircraft accomplish this through the inherent design of the controls, with no complex mixing, logic, or transitions required. The rotor and fixed wing controls operate in unison, all tied to the same control stick. At low speed, when the rotor is highly loaded but there's little airflow over the fixed wing controls, the rotor provides most of the control authority.   At high speeds, the rotor is unloaded but there's now high airflow over the fixed wing controls, so the fixed wing controls provide most of the control authority. The transition between those modes is a gradual transition of control authority from one set of control surface to the other, with no special inputs required from the pilot.

4.10   Software to autonomously control RPM of high inertia rotor while unpowered

Controlling rotor rpm manually puts a higher workload on the pilot, so it is preferable and potentially safer to automate this control. As discussed in Sections 4.4 and 4.6, the rotor angle is controlled through the means of a tilting mast. Developing the logic for the rotor rpm controller was challenging, requiring a fast response time under changing conditions, without the high inertia rotor overshooting the target. This development was an iterative process that required several software spirals and control law fine tuning to optimize the implementation.

5.   SR/C FLIGHT TEST RESULTS

Carter has tested several flying prototypes. The first of these was the CarterCopter Technology Demonstrator (CCTD – Figure 1), which was also the first aircraft to slow the rotor in flight to achieve an advance ratio of 1 (μ-1).The lessons learned from flying the CCTD were incorporated into the design of Carter's next prototype, the Personal Air Vehicle (PAV – Figure 2). The PAV has thus far exceeded μ-1 on eight separate flights, with continuous operations above μ-1 and a max advance ratio of 1.16. The PAV has also reached a top speed of 186 ktas and a max altitude of near 18,000 ft, with further testing expected to improve performance further.

Flight testing with the PAV to date has been mainly envelope expansion testing, and while these flights were not dedicated performance tests, stable periods were identified that were suitable for analysis. Data from these periods was analyzed, using measured thrust and known weight while also accounting for rate of climb or descent to determine L/D. Peak L/D was around 11. The flight test results were reviewed by the U.S. Army Aviation Applied Technology Directorate in

Cox [3], which validated the data reduction methodology.

5.1 Sensors / Measurements

Figure 9 shows a simplified schematic of the data collection system. Data collection is accomplished jointly by an off-the-shelf (OTS) Dynon Skyview System and two mission processors developed for the PAV. The Skyview system includes an SV-D1000 EFIS display, which collects standard EFIS data. In particular to the L/D analysis, it collects airspeed and altitude information from an SV-ADAHRS-200 module, which itself measures airspeed and altitude using the Pitot-static system. The EFIS unit outputs selected data over a serial output to the Carter Main Computer.
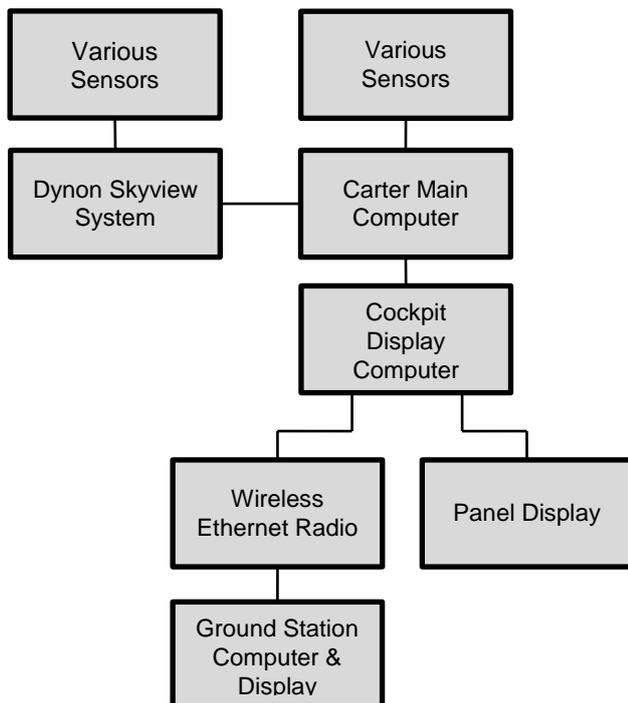

Figure 9. Simplified Data Collection Schematic

The Carter Main Computer receives data from the EFIS unit and collects data from other sensors that are not monitored by the EFIS unit, including propeller thrust. The propeller is mounted in such a way that thrust is reacted entirely against a doughnut shaped Teflon coated piston. An instrument quality pressure transducer (Measurement Specialties M5141-000005-250PG) was used to measure the pressure, and calibrated to thrust by applying a known load, with the calibration being repeated on a periodic basis.

In addition to handling all of the control logic and sending commands to various actuators, the Carter Main Computer outputs data to the Cockpit Display Computer. The Cockpit Display Computer drives a panel display for the pilots, records all data to an internal hard drive at a rate of 2 Hz, and sends the data over a wireless Ethernet radio to a ground station

computer. The ground station computer displays the data in real time during flight testing, and records a duplicate copy of the data on its hard drive.

5.2 Stable Period Determination

To find the stable periods, a program was written to examine the data and find periods that met given criteria as described in Lewis [8] and summarized in Figure 10.

Parameter	Value
Min Sample Duration, sec	20
TAS allowable change, ±mph	2
TAS allowable difference between start and end of period, mph	0
TAS minimum, mph	75
RPM allowable change, ±rpm	2
RPM allowable deviation from target, ±rpm	5
Min airspeed to check RPM target deviation	100
Power allowable change, ±HP	15
ROC allowable change, ±fpm	200
ROC min, fpm	-1,000
ROC max, fpm	2,000
Slip max allowable, g	0.1
Max overlap between periods, fraction	0.25

Figure 10. Stable Flight Criteria

5.3 L/D Calculation Method

The L/D calculations assumed a small climb angle and unaccelerated flight, such that lift is equal to weight:

$$\frac{L}{D} = \frac{W}{D}$$

The weight of the aircraft is measured on aircraft scales after any significant change to the aircraft configuration and assumed to be constant until the next significant change. This measured weight includes everything to represent the gross weight of the aircraft at engine startup, which was 4,316 lbs for all flights analyzed for this study. To determine aircraft weight in flight, fuel and water flow were calculated based on engine horsepower (the engine utilizes a water injection system to aid cooling), and integrated every half second to calculate the changing aircraft weight.

Drag was determined based on measured thrust, accounting for climb or descent rate. The method was power based – the power produced by the propeller would be equal to the sum of the power produced by drag and the power from altitude change.

$$P_{propeller} = P_{drag} + P_{ROC}$$
$$(T \times V) = (D \times V) + (W \times dh)$$

Solving for drag:

$$D = \frac{T \times V - W \times dh}{V}$$

With the weight and drag determined as described above, the L/D was calculated for each half second increment in a particular data range. The L/D calculation and measured data were then averaged over that range.

5.4 L/D Data for Multiple Flights

Representative L/D data from various test flights is shown in Figure 11. The data is from flights conducted between March and June, 2014. During these flights, the target rotor rpm vs. airspeed curve was changed several times to determine the curve that gave the best compromise of handling and cruise efficiency. As such, the data points in Figure 11 reflect variable rotor rpm. Additionally, the minimum rotor rpm for most of these flights was limited to either 120 or 125 rpm. In future flights, Carter plans to lower this minimum to 100 rpm, improving L/D values. Further improvements are expected from configuring and trimming the aircraft for cruise flight, since these data points are mostly from full power climb with cowl flaps wide open.

Direct measurement of fuel burn in cruise flight has shown the aircraft can achieve 14 miles per gallon fuel economy at 174 kts at 25,000 feet, enabling ranges of 1,800 miles with 45 minute reserves on 138 gallons of fuel.
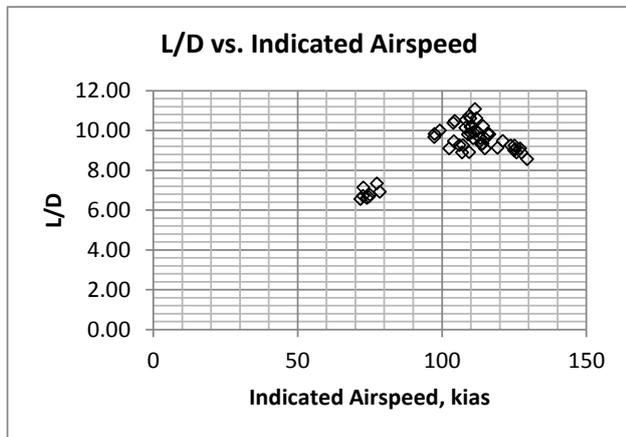

Figure 11. PAV L/D Flight Test Results at various Rotor RPMs

6. SR/C CARTERCOPTERS AND FUTURE VTOL PLATFORMS

Carter's SR/C technology can be applied to both hovering and non-hovering (jump takeoff / zero-roll landing) configurations. Specific mission requirements dictate whether or not to provide the full hovering capability. The slowed rotor technology is independent of hovering/non-hovering aircraft elements so both configurations provide high L/D / high cruise efficiency comparable to fixed-wing aircraft performance. Compared to a fixed-wing airplane, the additional rotor drag is offset by a smaller wing that is designed for efficient cruise flight rather than landing. The technology is scalable from small unmanned aircraft systems (UAS) up to an aircraft in the 767 size class.

From a weight and complexity perspective, the jump takeoff variants always have an edge over hovering variants. They do not require anti-torque capabilities nor a continuously loaded drive system. Consequently, complexity and related costs are much reduced and the overall empty weight of the configuration is less. However, for customers who require a full hovering capability, the technology still provides an order of magnitude improvement in cruise efficiency resulting in significantly reduced carbon emissions. The key enabler, again, is the slowing of the rotor in cruise flight and the dramatic reduction in drag as a result (Figure 4).

For example, Carter has developed a full hovering CarterCopter referred to as the CC-221 for the offshore oil platform service market and other missions requiring similar capabilities (Figure 13). It carries 2 pilots and 21 passengers with a total cargo volume of 290 ft³. A high capacity configuration could seat 24 passengers. The aircraft has a 70' diameter rotor, and two 112" propellers. It is powered by twin GE CT7-8A6 turboshaft engines sufficient for a max continuous speed of 313 ktas , a service ceiling of 36.3k ft, and a hover out of ground effect (HOGE) ceiling at max gross weight of 6275 ft (Carter & Lewis [4]).
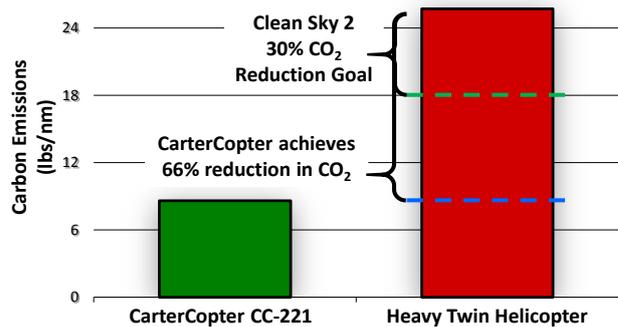

Figure 12. CC-221 Heavy Twin CarterCopter CO2 emissions per nautical mile versus Heavy Twin Helicopters

As was done with light single helicopters, sampling the market's heavy twin helicopters currently performing the majority of the deep rig (long range) offshore oil support missions, the average fuel burn is 8.14 lbs/nm, which equates to 25.72 lbs of CO_2 emissions per nautical mile. Figure 12 illustrates heavy twin
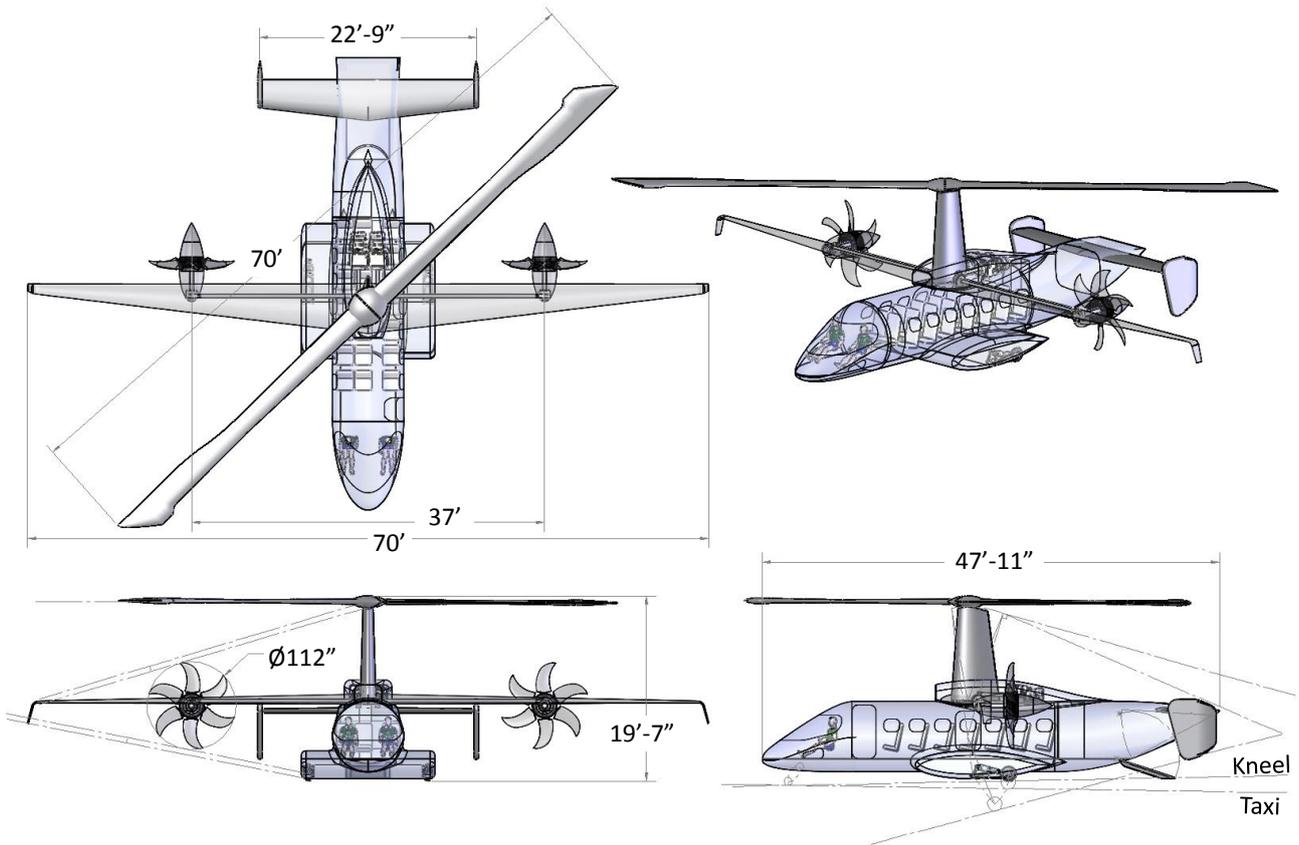
Figure 13. CC-221 Three-View & Dimetric

CarterCopter emissions represented by the CC-221 cruise performance versus the average CO_2 emissions for today's heavy twin fleet. As can be seen, the CarterCopter achieves over twice the reduction in CO_2 emissions as that targeted by Clean Sky 2.

From small UAS to heavy twins such as the CC-221 to jumbo aircraft such as Carter's Joint Heavy Lift (JHL) concept (Figure 14), which has a 150 ft diameter rotor, and is capable of carrying an Abrams tank, or 200 troops, the technology delivers significant utility and operational capability in a very environmentally friendly manner.
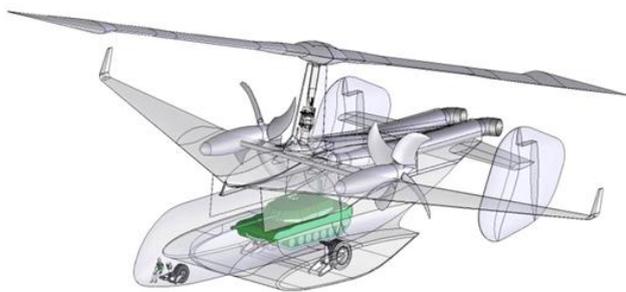

Figure 14. Carter's Joint Heavy Lift Concept

Carter has developed various methods of providing counter torque in hovering configurations. Because CarterCopters require forward thrust independent of the main rotor, the source of this thrust can be used to provide the counter torque without using a tail rotor. With conventional turboshaft or turboprop engines, the engines will drive propellers, with the propellers mounted far enough out on the wings to have an adequate moment arm for countering rotor torque. The majority of counter torque will come from the propeller producing thrust in the normal direction, but hover efficiency can be improved by operating the opposite propeller at negative pitch for reverse thrust, partially unloading the primary propeller. This is the method used on the CC-221.

When a suitable engine is available, counter torque can be provided by jet thrust, with propellers used for fine yaw control. This is the method used on Carter's JHL concept, using the Pratt & Whitney F135 engine developed for the Joint Strike Fighter. The jet exhaust is ducted to the rear of the aircraft, and deflected to the side for hover operations, or aimed straight back for cruise. Because the propellers aren't required to generate a high yawing moment, they can be located further inboard on the wings, allowing the wings to be easily folded outboard of the props, and also allowing a larger prop diameter while still maintaining adequate clearance to the rotor. With folding wings and a 2-bladed rotor, the aircraft can be stowed compactly.

The combination of large propellers and gas turbine engine acts effectively as a high bypass ratio turbofan, with the propellers providing high thrust at low speeds, then being partially unloaded at high speeds where the jet exhaust provides the balance of thrust. To further improve the efficiency of the propulsion system, the propeller rpm is reduced as speed increases through a multi-speed automatic transmission located on the high speed/low torque output of the gas turbine engine. This allows the tip speed of the propeller to be kept near its optimum through all flight conditions.

7. CONCLUSIONS

A new era of aviation is now possible with Carter's SR/C technology. Runway independent aircraft (to include full hovering configurations) possessing efficiencies more akin to fixed-wing aircraft promise to deliver a cleaner, greener, and safer VTOL capability that exceeds the environmental goals of Clean Sky 2. Carter's jump takeoff light single has demonstrated CO_2 emission reductions of 80% compared to representative helicopters in the market. Carter's full hovering CC-221 is predicted to achieve CO_2 emission reductions of 66% when compared to representative heavy twins performing today's offshore oil rig support mission. And, all of this is accomplished with 15-20 EPNdB less noise than conventional helicopters. CarterCopters have gone beyond Clean Sky 2 and promise more capable and more environmentally friendly vertical-lift in the future.

8. REFERENCES

[1] "Clean Sky 2: developing new generations of greener aircraft," Clean Sky website, 2014, Cited June 18, 2015,
http://cleansky.eu/sites/default/files/documents/cs2/cs2_commission_factsheet.pdf.

[2] Harris, F.D., "The XV-1's Rotor System," AHS 4th Decennial Specialist's Conference on Aeromechanics, 2004. AHS 4th Decennial Specialist's Conference on Aeromechanics, San Francisco, CA, January 2004.

[3] Cox, J.A., "Assessment of Current State of Technical Development of the Personal Air Vehicle Developed by Carter Aviation Technologies, LLC," Aviation Development Directorate, Aviation Applied Technology Directorate, Flight Test Branch, 2015.

[4] Carter, J., Lewis, J.R., "CarterCopter Technology Goes Offshore: Commercial Variant with Full Hover Capability", American Helicopter Society Forum 71, Virginia Beach, Virginia, 2015.

[5] Foster, R. D., "A Rapid Performance Prediction Method for Compound Type Rotorcraft," WADC TR 55-410, 1957.

[6] Lewis, J.R., Carter, J., Peryea, M., Pichon, E., "Carter Personal Air Vehicle," American Helicopter Society Specialists' Meeting, Fort Worth, Texas, October 2008.

[7] Carter, J., Lewis, J.R., "Rotor Collective Pitch vs Mu to Control Flapping and Mast/Rotor Tilt to Control Rotor RPM," United States Patent 7,448,571, November 11, 2008.

[8] Lewis, J.R., "PAV SN01 Preliminary Flight Test Performance," Carter Aviation Technologies DOC 11G-FLT-0-004-A, Wichita Falls, Texas, 2014.