

Greener Helicopters

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1 INTRODUCTION

Helicopter operations present multiple environmental challenges in a world where industrialized nations are adopting stricter regulations on air pollution and noise. Helicopters and other types of rotorcraft have the unique capability of taking off vertically and hovering efficiently for extended periods of time, enabling missions such as emergency medical service, search and rescue, infrastructure maintenance, and accessing remote locations. They also have the potential to supplement commercial passenger flights without requiring major infrastructure improvements at airports. In order to continue filling these vital roles in the future, new rotorcraft will need to be designed for minimal environmental

impact. Historically, in VTOL (vertical takeoff and landing) vehicle design, environmental performance, particularly from an emissions standpoint, has been largely overlooked. Changing attitudes and increased regulations on emissions and noise have recently fostered interest in greener helicopters. Europe's Clean Sky program (Clean Sky, 2014) includes a Green Rotorcraft Integrated Technology Demonstrators (ITD) component led by Agusta Westland and Airbus. The Green Rotorcraft ITD has three top-level objectives:

- Reduce CO₂ emission by 25–40% per mission (for rotorcraft powered respectively by turboshaft and diesel engines).
- Reduce the noise perceived on ground by 10 EPNdB or reduce the noise footprint area by 50%.
- Ensure full compliance with the REACH directive, which protects human health and environment from harmful chemical substances.

Under Clean Sky, vehicle components are also targeted to have green life cycles, from design to disposal (or recycling). In the United States, the Federal Aviation Administration (FAA) has sponsored research under the Continuous Lower Energy, Emissions and Noise (CLEEN) program with goals for noise, emissions, and fuel burn but demonstrators are not in current plans.

The US rotorcraft community as a whole does not have nationally recognized green goals equivalent to Clean Sky; however, for US rotorcraft to be competitive in the European

market and the new markets in Asia and South America, the Clean Sky goals cannot be ignored. NASA's Revolutionary Vertical Lift Technology project includes ongoing research dedicated to the characterization and design of low-noise rotors and is evaluating propulsion technologies that would reduce emissions and fuel burn.

One approach to reducing or eliminating emissions is to radically redesign the powerplant. While there are many examples of hobby-sized rotorcraft powered by electric motors, full-scale rotorcraft are traditionally powered by either turbine or piston engines. Internal combustion engines have their peak efficiencies at low torque and high rotational speed. Large rotors require high torque and low RPM, necessitating heavy gearboxes to transmit power from the engine to the rotor.

There are new powerplant concepts under development that replace the internal combustion engine with one or more electric motors. These motors can be powered by various nonpolluting energy sources, such as batteries and fuel cells, eliminating greenhouse gas emissions altogether. Hybrid electric powerplant designs have also been proposed, where a gas turbine or a reciprocating engine powers a generator to deliver electrical power to the motors, allowing the engine to constantly run at its peak efficiency and minimum emissions. Multispeed gearboxes are under development to allow optimum engine efficiency in different flight regimes; a feature especially important for rotorcraft designs such as tiltrotors and compound helicopters that slow their rotors during cruise.

Rotor noise can be reduced by affecting the source of the noise or by following noise abatement procedures during operations. In addition to minimizing the flight time over noise-sensitive areas of the community, procedures for turns, descent, and takeoff can reduce external noise. The main rotor(s) of a helicopter is the primary source of noise that annoys people, and methods for reducing main rotor noise have focused on techniques for weakening the rotor blade tip vortices or altering their trajectory so that the vortices do not interact with the other blades. Reduced rotor tip speeds and tailored tip shapes have also contributed to lowering helicopter noise.

Software tools for designing and analyzing rotorcraft are under constant development by government agencies, industry, and universities. These tools allow engineers to rapidly generate conceptual rotorcraft designs to meet certain mission and performance specifications. Performance analysis of existing rotorcraft is also possible, making it easy to calculate fuel burn and emissions for a particular mission. The capability to quickly and accurately model advanced propulsion systems allows engineers to design rotorcraft concepts with a diverse range of propulsion architectures.

The use of "green metrics" to measure the environmental performance of rotorcraft is another area of active research. The simplest option is to only look at CO₂ emissions, but there are other types of greenhouse gas emissions produced by internal combustion engines. Various metrics can be used to aid in the design of future rotorcraft to balance operating and purchase costs with emissions and noise.

The remainder of this chapter will expand on the topics of propulsion concepts, noise-reducing technologies, VTOL-sizing tools, climate metrics for green design, and a notional transportation system using non-carbon-fueled VTOL aircraft.

2 PROPULSION SYSTEMS

Propulsion performance characteristics have a strong impact on vehicle design. Fewer larger engines tend to have higher component and overall efficiencies and can have improved power-to-weight ratios. This fact, combined with the complexity and weight of drive systems and gearboxes, has led helicopter designs to evolve to a single or coaxial main rotor powered by one or two engines. However, with the advent of very efficient, high power-to-weight electric motors and generators, combined with increased battery capabilities, the design space for VTOL vehicles has been greatly increased in terms of vehicle configurations and potential missions.

2.1 VTOL Vehicle Designs with Green Propulsion Systems

To improve understanding for component design, interactions, and requirements, many efforts are starting with "conventional" helicopter design concepts and replacing hydrocarbon-fueled engines and fuel tanks with electric motors, power management and distribution (PMAD) systems, and battery packs. The NASA Hopper study, discussed in further detail later, envisioned 30-passenger tandem-rotor vehicles to give quick and flexible extensions of commuter transportation, and is especially relevant where traditional train or bus routes are impeded by terrain or other factors.

To explore system design with real electric propulsion hardware, Sikorsky developed their Firefly technology demonstrator. Starting with the Sikorsky S-300 vehicle, the gasoline reciprocating engine and fuel system were replaced with specially designed electric motor, PMAD, and battery packs. Although the present state-of-the-art all-electric technology limits the duration and range of this vehicle, much was and still can be learned about system design and

requirements, including thermal management, fault detection/isolation, and redundancy.

Another all-electric helicopter concept under development is the Volocopter VC200. Instead of a single main rotor with counter-torque tail rotor, the VC200 uses multiple individually controlled electric motor rotors, a system commonly referred to as distributed propulsion. These smaller rotors turn at a much higher RPM than the large rotors of traditional helicopters. Power and torque requirements for each rotor are small (reduced rotor weight), which facilitates the use of multiple, smaller, and lighter electric motors for redundancy, while maintaining or improving power-to-weight ratio and efficiency of the propulsion system. Efficient hover, flight control, and VTOL operation are obtained through the individual control of the various motor/rotor sets.

Many vertical lift missions have minimal hover requirements; in these cases, concepts with greater similarity to advanced fixed-wing aircraft are being studied and developed. The vehicles are envisioned to use distributed propulsion components to enable VTOL capabilities, while converting into a more traditional, fixed-wing aircraft configuration for the bulk of the mission. NASA's Greased Lightning demonstrator is an example of this type of concept. Although hover performance can be seriously degraded by this vehicle design choice, vehicle speed, range, and aerodynamic efficiency are greatly improved during the dominant cruise portion of the mission. VTOL capability further enhances vehicle operational flexibility and user mobility potential by using takeoff/landing areas more convenient to the user, rather than being constrained to an airport runway.

2.2 Types of Green Propulsion Systems

For motive force, rotorcraft systems generally include engines/motors, rotors, and the gearbox/drive systems to connect them. The design for each of these three parts affects others' overall performance. At present, the dominant engine choice for most, especially larger vehicles, is a gas turbine (turboshaft) engine. These engines are fairly simple in concept, smooth, dependable, and have high power-to-weight and power-to-volume. However, current large turboshaft helicopter engines are roughly 25% or less thermally efficient; smaller engines have higher losses and may be only about 15% efficient. At less than full power, engine efficiency falls quickly. Gas turbines rotate at a fairly high RPM, which increases as engine size decreases. A gearbox is used to significantly reduce engine RPM to match rotor requirements, adding to propulsion weight, complexity, and maintenance. Many alternatives to traditional turbine engines are becoming available, with constantly improving technology to reduce

weight, improve efficiency, and reduce harmful emissions. Nagaraj and Chopra (2014) provide a survey of alternative helicopter propulsion systems, and the following section describes some of the promising options.

Gasoline reciprocating engines can match or exceed gas turbine engine efficiencies, especially at lower power levels (less than 400 hp). Gasoline engines are about 20–30% efficient and maintain efficiency levels for some reduction from full power. Their significantly lower power to weight (generally 0.5 hp lb^{-1} .) makes them impractical for large aviation power requirements. Previous aviation gasoline engines used high-octane (often leaded) gasoline for improved performance and reliability. Lead emissions and exposure have serious health consequences; therefore, leaded gasoline is being regulated out. An alternative to gasoline is the diesel engine, which can have efficiencies of 40–50% or more, while maintaining efficiency at partial power. Because diesel engines use compression ignition, no high-voltage ignition system is required, improving reliability compared to gasoline engines and reducing interference to other electrical devices. Diesel engines run at higher compression ratios and maximum pressures, requiring a stronger engine design. New materials and manufacturing have made them a viable choice to replace gasoline and some small gas turbine aviation powerplants, enabling significant reductions in fuel usage and CO₂ emissions. With high efficiencies, but low power-to-weight ratio, diesel engines are best suited to vehicles with lower power requirements and long duration/range requirements.

With advanced materials and designs, electric motors (and generators) are becoming available that can match or exceed the power-to-weight ratios of advanced gas turbines. This is achieved with high RPM, low torque devices, which contrasts with the low RPM, high torque requirements for conventional rotorcraft vehicles. Motor efficiencies are above 90%, significantly better than gas turbine or reciprocating engines, and electric motors can maintain (or improve) efficiency at reduced power levels and RPM. Another important design feature for electric motors is scalability. For gas turbine or reciprocating engines, thermal efficiency is generally improved with engine size and power; however, electric motor efficiency and power-to-weight ratio are almost independent of size (with weight being more closely aligned with torque). This reinforces design concepts that use multiple high-RPM electric motors.

In addition to the design of the motive force, the optimum vehicle design must include the energy storage and generation to meet mission requirements. Traditional hydrocarbon (jet, gasoline, or diesel) fuels have been used for transportation systems for many years because of their high energy content per mass and volume, established infrastructure for access and availability, and fast and easy refueling. These fuels tend

4 Vehicle Design

to fall in a narrow range of pounds of CO₂ produced per pound fuel or energy content. There are few traditional hydrocarbon fuels that would significantly improve on emissions or energy per mass properties. Alternative fuel studies using methane or hydrogen have identified potential reduction of CO₂ and other emissions produced during actual vehicle use. However, both methane and hydrogen-fuelled vehicles are penalized by low fuel energy density. Figure 1 shows the energy density and specific energy for a variety of fuels. Fuel energy density can be improved by compressing methane and hydrogen fuel in gas phase or liquefying into the cryogenic state (at additional energy, cost, safety/handling issues, and fuel system complexity).

Aircraft continue to evolve to more electric systems because of improvements in efficiency and reliability, with batteries as an integral part of that evolution. From Figure 1, batteries look like an unattractive option for energy storage; however, batteries continue to improve with respect to power and energy density, safety, number of discharge/recharge cycles, cost, cell chemistries, and so on. Battery system optimization for a particular vehicle and mission is a complex trade-off among all of these attributes. All-electric aircraft with batteries is a compelling goal due to low noise, no exhaust gases, and battery energy transformed to motive power generally exceeding 80% efficiency, where competing systems struggle to reach 50% efficiency.

Fuel cells are electrochemical devices that directly convert chemical energy of a fuel (typically hydrogen) into electricity. A fuel cell is not a combustion device, so it is not limited to Carnot efficiency and, therefore, has the potential for higher

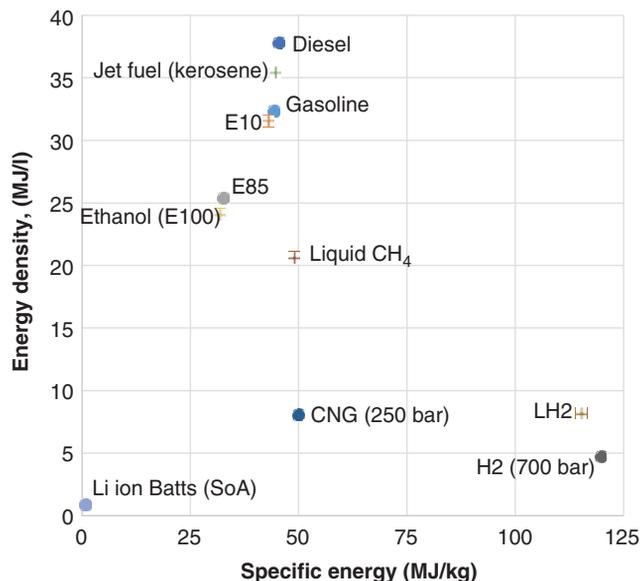


Figure 1. Energy density and specific energy of various fuels. (Reproduced from NASA.)

efficiency than gas turbine or reciprocating engines. A recent study examined the propulsion requirements for a manned ultralight utility helicopter powered by fuel cells (Datta and Johnson, 2014). This study showed that a fuel cell propulsion system is feasible, but that further improvements to the system components are needed to match the performance of an internal combustion engine. Automotive and stationary power systems continue to develop fuel cells for power generation, although the requirements are different in many aspects, and are less stringent than aviation needs. Power density for fuel cell systems is presently limited by the material properties/requirements for the reaction membrane or cell chemistry and ancillary systems (balance of plant) required for thermal management, fuel and oxidizer management, and so on.

Another energy storage idea gaining new interest is flywheels. Flywheels use rotational inertia to store energy. Improved bearing choices (including magnetic bearings), new materials, and improved sensors/controls have reinvigorated the idea of using flywheels for energy storage. Improved bearings can facilitate increasing flywheel rotational speeds and energy density, also reducing friction losses and heat generation. Advanced, high-strength materials enable higher flywheel rotational speeds, increasing energy density during use, and improving environmental impact during manufacturing and at end of life.

A possible interim solution to various green, limited energy density storage systems, such as batteries and flywheels, is the option of adding a fuelled engine-generator or “range extender” system. Range extenders are especially suited for vehicles/missions that have a rare or nontypical, extended-duration power requirement. Sizing a battery or flywheel alone to meet those longer mission requirements would strongly and adversely impact the vehicle/mission performance for the standard mission. Since the combustion-powered sustainer system would operate at essentially constant conditions, its performance can be optimized for maximum efficiency and minimum emissions during the extended segment of the mission.

The hybrid turboelectric system is another potential propulsion option for power and energy requirements that cannot be effectively achieved with other energy storage systems, or as an interim system to an all-electric vehicle. Hybrid turboelectric systems are envisioned for large vehicles, with high-power levels for long durations, as well as using electric, distributed propulsion because of favorable propulsion/vehicle synergies. Hybrid turboelectric systems might be considered a special case of the sustainer/range extender system, where the gas turbine–electric generator system is always present and operating at optimum efficiency over the entire mission. Emergency or contingency

power requirements could be met with batteries or other energy storage systems. The actual mix among various energy generation/storage systems is highly dependent on system capabilities and mission requirements.

2.3 Ongoing Propulsion Research within NASA

Work continues on gas turbines to further improve efficiency and apply these gains to rotorcraft design (Snyder, 2014; Hendricks, Jones, and Gray, 2014). There are still significant gains to be achieved through turbomachinery component efficiency. Improved strength and maximum temperature materials can realize benefits in both fuel efficiency and power-to-weight ratio. Applying these current advanced technologies into a new generation of higher overall pressure ratio engines can reduce specific fuel consumption 25% compared to current engines. Turbomachinery efficiency gains enabled by further design, material, and manufacturing improvements under exploration suggest an additional 16–25% specific fuel consumption reduction. Combustor design changes enabling lean combustion are projected to reduce cruise NO_x production by up to 80% relative to 2005 best in class (Chang *et al.*, 2013). Variable-speed power turbine technology, which can mitigate severe engine power turbine efficiency decrements at reduced RPM, enabling the rotor to slow down and improve rotor propulsive efficiency by 2–3%, continues to be explored (Welch *et al.*, 2012). A recent study employing heat exchangers and regeneration reported a 35% reduction in mission fuel burn and CO_2 is possible, but results in a two to three times increase in NO_x (Fakhre *et al.*, 2013).

Work on the design, control, and thermal management for electric motors and generators continues (Choi *et al.*, 2014). Although significant progress has been made in power-to-weight ratio for high-RPM, low-torque motors, many applications would be better served by lower RPM and higher torque, without adding a gearbox. Research is also exploring better motor control and response to enhance vehicle performance and control, through ancillary work on PMAD for robustness and redundancy.

Gearbox and drive system work continues to look at innovative gear tooth geometries, hybrid gears, advanced materials, and multispeed systems to better match speed and torque between motive force producers (engines, motors, etc.) and users (rotors, generators, etc.) (Roberts *et al.*, 2013; Stevens, Handschuh, and Lewicki, 2008). Gearbox and drive train efficiencies are high (>95%), but gains are still realizable for weight, reliability, and maintenance requirements.

Fuel cell research continues to exploit new materials and chemistries to reduce the need for strategic materials, improve response to transient power demands, power per weight and

volume, and reduce the need and penalties for balance of plant. Results so far suggest more research is needed to identify the combination of systems and technologies that will achieve the stringent power, weight, and volume requirements required for primary aerospace propulsion.

3 ACOUSTICS

Despite all the unique capabilities that rotorcraft vehicles provide in the area of public service, noise continues to be a major deterrent to increased use of rotorcraft in both urban and remote areas. In urban areas, there is a growing opposition to helicopter operations that are not within the purview of the government, such as tourist flights, air taxi services, and news reporting. There are a number of instances where the public reaction to noise is leading to legislation to regulate rotorcraft noise. For example, in Los Angeles, California, in 2011 legislation was discussed to target “noise from low-flying helicopters above Los Angeles neighborhoods” (Now, 2011). The primary reasons stated for such legislation were issues of safety and noise. More recently, in February 2013, H.R. 456 “Los Angeles Residential Helicopter Noise Relief Act of 2013” (Schiff, 2013) was introduced in the House of Representatives and a related bill (Feinstein, 2013) was introduced in the Senate. These bills, if passed, would direct the Administrator of the FAA to prescribe regulations for helicopter operations in Los Angeles County, including prescription of helicopter flight paths and altitudes to reduce helicopter noise. In some cases, regulations are already in place. For example, for Long Island, NY, there is legislation that requires helicopter pilots to use the New York North Shore Helicopter Route in order to reduce “helicopter overflights and attendant noise disturbance of nearby communities” (FAA, 2014; 14 CFR 93 Subpart G (93.101)).

Helicopters operating in remote areas are not immune to regulation either. For example, special flight rules as part of the FAA Regulations (14 CFR 93 Subpart U) dictate where and how helicopters can be operated in the vicinity of the Grand Canyon National Park (GCNP). These regulations specify items such as minimum flight altitudes for various areas of the park. Moreover, these regulations create a “GCNP Quiet Aircraft Technology Designation,” which is based on number of passengers, rather than the FAA Certification requirements that are based on vehicle weight.

3.1 Types of Rotorcraft Noise

The noise we hear from a helicopter in flight is the result of a combination of complex aerodynamic and structural

dynamic phenomena. This noise is a function of the steady and unsteady aerodynamics on the rotating wings as well as the motion of the rotating wings relative to the position and motion of the location where noise is being measured (i.e., the “observer location”). For example, in FAA Noise Certification requirements, the “observer” locations are specified as three specific microphone locations near the ground where noise from three different flight conditions (takeoff, flyover, and approach) for a vehicle-specific flight condition are measured. The noise metric used to define FAA Noise Certification standards is the Effective Perceived Noise Level (EPNdB) measured in decibels. Even though EPNdB is the standard metric by which many aircraft noise limits are defined with regard to FAA certification, this “certification metric” does not always correlate well with the level of public acceptance of rotorcraft. For example, all of the rotorcraft vehicles covered by the above-mentioned New York North Shore Helicopter Route regulation already meet requirements for FAA Noise Certification. Yet, they are still being further regulated to limit noise over communities. To begin to understand this issue, a brief overview of rotary wing noise mechanics is warranted. Figure 2 shows the various sources of helicopter noise.

In general, the noise from a helicopter is composed of both discrete frequency noise and broadband noise. Discrete frequency noise is often dominant in lower frequencies and is usually impulsive in nature. People are generally more annoyed by impulsive noise than by broadband noise. “Blade–vortex interaction (BVI)” noise is a discrete (impulsive) noise characteristic that is generated when a rotor blade and a strong vortex interact closely in a parallel manner. BVI

can be a strong noise mechanism in low-speed, descending flight conditions and in high-speed level flight. Other types of discrete frequency noise are thickness noise resulting from displacement of the air around the thickness of the blade; high-speed impulsive (HSI) noise resulting from transonic flow around the rotor blade; and steady (or unsteady) loading as the blades move relative to the observer. BVI and steady/unsteady loading noise are generally directed below the rotor, while thickness noise and HSI noise are generally directed forward of, and near the plane of, the rotor.

Broadband noise is a nonimpulsive phenomenon that occurs over a wide range of frequencies (usually higher frequencies than those seen in impulsive noise). Broadband noise sources include blade–wake interaction (BWI), where a rotor blade encounters a vortex at an oblique angle, and turbulence ingestion noise (TIN), where atmospheric turbulence enters the rotor system. Broadband noise also encompasses “self-noise,” which covers a wide array of phenomena such as trailing edge noise, several types of laminar and turbulent boundary layer noise, and noise due to a vortex generated at the blade tip.

All of the above noise sources (among others) contribute to the frequency content of noise at an observer location. The EPNdB metric was originally developed to quantify fixed wing vehicle noise and emphasizes frequencies where the human ear is most sensitive. There are corrections included in this metric to account for discrete frequencies (tones). However, rotorcraft noise is often dominated by impulsive noise, which is relatively low frequency. These low frequencies are de-emphasized by the EPNdB metric, but are often a source of public annoyance, leading to the situation of a helicopter

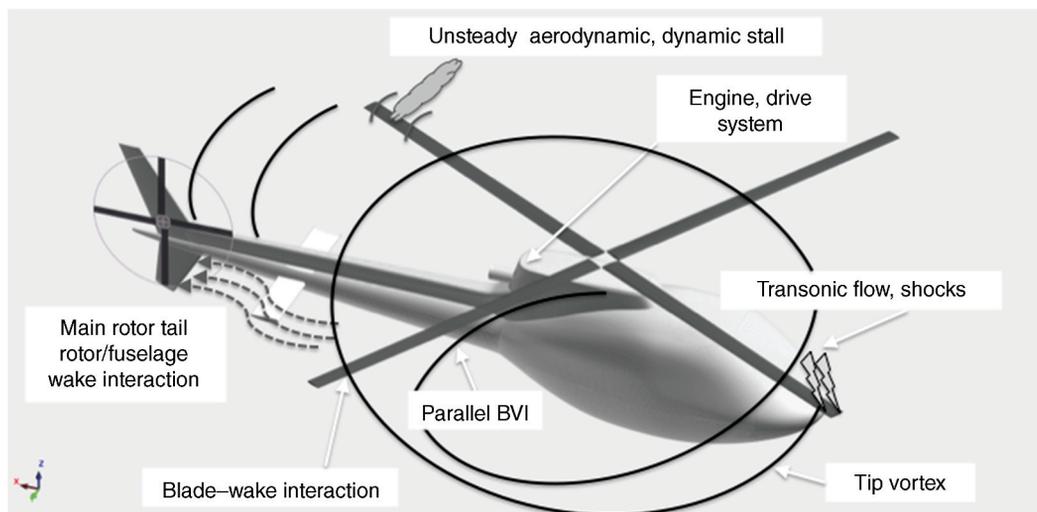


Figure 2. Examples of sources that contribute to helicopter noise. (Reproduced from NASA.)

that meets the FAA Noise Certification requirements, but is prohibited from flying over certain areas due to the noise it generates.

3.2 Reducing Rotorcraft Noise

Attempts to reduce helicopter noise have generally fallen into two categories: design and flight path management. The design category is further subdivided into passive and active methods. Passive methods can be exemplified by rotor blade planform changes that range from subtle changes in twist to radical changes in planform shape. For example, two NASA planform designs include rotor blades such as the “Dogleg” blade (Brooks, 1996) and the “Wavy” blade (NASA Tech Briefs, 2004), shown in Figures 3 and 4, respectively. Both designs primarily target the reduction of BVI noise. Examples of active methods have included such items as higher harmonic control (HHC) (van der Wall *et al.*, 2003), individual blade control (IBC) (Jacklin *et al.*, 1995), active twist rotor blades (ATR) (Wilbur *et al.*, 2000), and active flaps (Lau *et al.*, 2010). These active methods have often been used to target several noise mechanisms, such as BVI noise. Slowing the rotation of the rotor is yet another approach for reducing helicopter noise. NASA continues to investigate approaches for significantly (on the order of 50%) varying the main rotor speed via the engine and/or multispeed drive trains. Ongoing work on variable speed drive trains and power turbines to achieve this reduction were discussed in the previous section.

Most of the above technologies have been examined in a wind tunnel environment, in model scale, and/or in full-scale rotors. Some of the technologies have also been flight tested. For example, a BK117 helicopter has been flown (Dieterich, Enenlk, and Roth, 2006) with active flaps to control noise and flight characteristics. A radial swept blade known as the Blue Edge (Rauch *et al.*, 2011) has also been flight tested. Despite

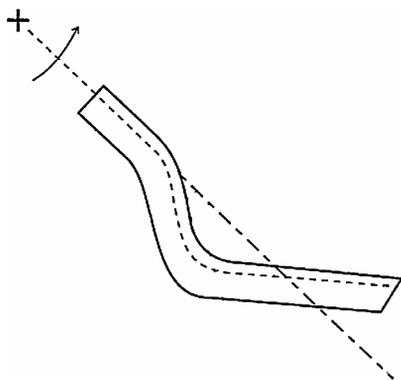


Figure 3. “Dogleg” blade planform. (Reproduced from NASA.)



Figure 4. Wavy planform rotor on model helicopter in wind tunnel. (Reproduced from NASA.)

the wind tunnel and flight testing of many of these technologies, few, if any, have been incorporated into a production vehicle.

The other part of noise reduction efforts has focused on flight path management. Management of flight paths was recognized since the late 1960s as an effective method for significantly reducing helicopter noise. For example, a Vertiflite article by Dennis Halwes in 1971 (Halwes, 1971) identified a relation that has become known as the “fried egg plot” and is still used to date. This plot identified the high-noise flight regimes for a generic midweight helicopter as a function of airspeed and descent–climb rate. Halwes (1971) also identifies flight paths that could avoid these high-noise flight regimes. These relations and flight path management strategies are still seen in the *Fly Neighborly Guide* published by the Helicopter Association International (HAI), which provides noise abatement procedures for a variety of helicopters (<http://www.rotor.com/Operations/FlyNeighborly/FlyNeighborlyGuide.aspx>). Figure 5 shows an example fried egg plot; the plot is a direct descendant of the original figure from Halwes (1971).

Many extensions of the flight path management strategy above have been explored in the last few decades. NASA, for example, has created measured databases of noise characteristics for a wide range of helicopters to aid in the optimization of flight paths for noise mitigation. Measured helicopter noise databases in this context range from steady-state flight paths (e.g., level flight, constant angle descents, etc.) for the XV-15 tiltrotor research aircraft (Conner *et al.*, 2000) to maneuvering flight conditions on a Bell 430 aircraft (Watts *et al.*, 2014). Although flight tests have shown that noise can be reduced through flight path management, most of the methods that show noise reduction benefits have not yet been deployed.

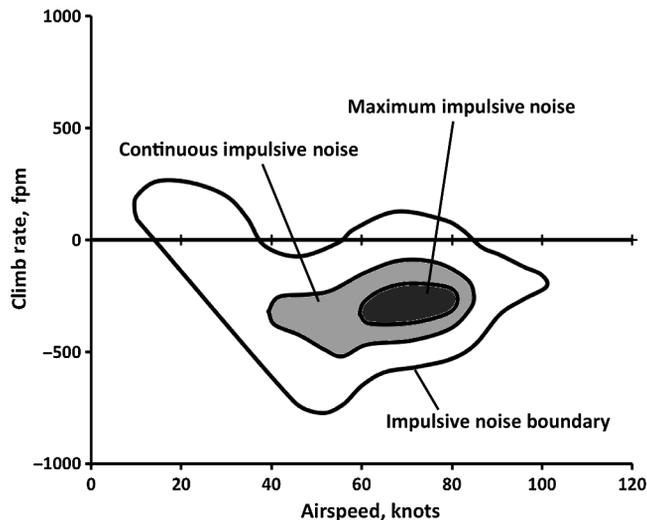


Figure 5. Example fried egg plot showing main rotor impulsive noise boundaries. (Reproduced from NASA.)

4 CONCEPTUAL DESIGN

Reducing environmental impact of rotorcraft requires consideration of new propulsion architectures, beyond the conventional configuration of turboshaft or reciprocating engines burning hydrocarbon fuel, connected to rotors through a mechanical transmission. Conceptual design and analysis software can greatly enhance the ability of engineers to efficiently evaluate many vehicle configurations and propulsion architectures.

4.1 Rotorcraft Design Software

NASA Design and Analysis of Rotorcraft (NDARC) (Johnson, 2010, 2014) is a computer program for rotorcraft conceptual design and analysis. The design task sizes the rotorcraft to satisfy a set of design conditions and missions. The analysis tasks include off-design mission performance analysis and flight performance calculation for point operating conditions.

To achieve flexibility, NDARC constructs a rotorcraft from a set of components, including fuselage, wings, tails, rotors, transmissions, and engines. For efficiency of program execution, each component requires a surrogate model for performance and weight estimation. Higher fidelity component design and analysis programs as well as databases of existing components provide the information needed to calibrate these surrogate models, including the influence of size and technology level. Confidence in the synthesis and

evaluation results depends on the accuracy of the calibrated component models.

The propulsion system components that consume fuel can be characterized in three ways:

- Transferring power by shaft torque (engines and motors)
- Producing a force on the aircraft (jets)
- Generating energy for the aircraft (chargers)

Engines and rotors are connected to a mechanical drive train. The “engines” category includes turboshaft and reciprocating engines, compressors, motors, generators, and generator-motors. The “jets” category includes turbojet and turbofan engines and reaction drive systems for rotors. The “chargers” category includes fuel cells and solar cells. Each engine, jet, and charger is associated with a fuel type and a fuel tank system. Figure 6 shows the general architecture of propulsion systems built within NDARC.

Fuels can be characterized by whether the quantity stored and used is measured in weight or energy. The fuel container has a capacity and a weight. Fuels for which the weight changes include jet fuel, gasoline, diesel, and hydrogen. Fuels for which the weight does not change include electric energy (batteries, capacitors) and kinetic energy (flywheels).

Many propulsion architectures can be constructed from these components. Variations in the number and distribution of the rotors, engines, motors, generators, and other components lead to a large range of potential configurations. The task of the conceptual design program is to identify the optimum configuration for the new generation of green rotorcraft.

Another rotorcraft conceptual design tool, currently under development by the French Aerospace Lab, ONERA, is CREATION (Concepts of Rotorcraft Enhanced Assessment Through Integrated Optimization Network) (Basset *et al.*, 2012). Like NDARC, CREATION integrates reduced-order surrogate models into the rotorcraft design process. CREATION also includes the option to directly use higher order engine and aerodynamic models in its analysis, as well as integrating formal optimization routines. Recently, this software has been exercised to optimize a helicopter with acoustic

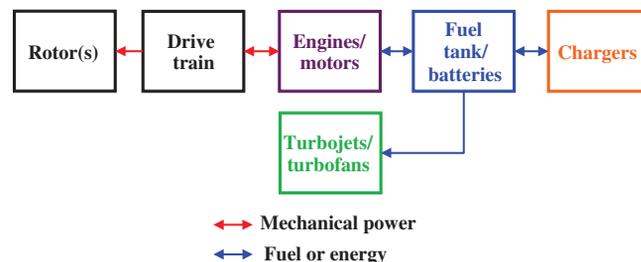


Figure 6. Generalized propulsion system architecture for NDARC. (Reproduced from NASA.)

footprint as one of the objective functions (Basset *et al.*, 2014). This functionality allows for a rotorcraft design that is optimized for environmental performance as well as traditional cost drivers, such as empty weight and fuel burn. A similar rotorcraft conceptual design code, called COMRADE (COMputer-aided Rotorcraft Assessment and Design), is under development by the German Aerospace Center, DLR. The COMRADE code is integrated into the RIDE (Rotorcraft Integrated Design and Evaluation) design environment, which allows for more detailed investigation of various rotorcraft components (Lier *et al.*, 2014).

4.2 Applying “Green Metrics” to Rotorcraft Design

Integrating environmental performance in the rotorcraft design process is possible, but one first needs to choose or define the metrics that will be used to measure environmental impact. The challenge is to find metrics that are comprehensive but also have acceptable levels of uncertainty. The easiest thing to calculate is CO₂ emissions; however, such a simple metric ignores the effects of other emissions such as NO_x. Civil transport rotorcraft concepts were designed and evaluated with the NDARC software in (Russell and Basset, 2015) using the average temperature response (ATR) metric.

ATR is a recently developed metric that specifically targets aircraft emissions (Dallara, Kroo, and Waitz 2011). This metric is measured in terms of global mean temperature change caused by operation of a particular aircraft. This temperature change is a function of the heat trapped by each emitted

pollutant species. ATR can be expressed in relative terms, where the ATR for one design is divided by that of a baseline design. This allows for easy comparison between aircraft.

While future rotorcraft are likely to be designed to balance operating costs, purchase costs, and environmental performance, Russell and Basset (2015) separated them in order to show the effects of designing large civil rotorcraft concepts to different metrics. Figure 7 shows the effect of cruise altitude on the relative ATR as well as on the fuel burn. The results show that minimum environmental impact is obtained by flying lower and slower than the minimum fuel burn solution. This result is chiefly due to the warming effects of NO_x, which are stronger at higher altitudes.

One of the challenges to calculating emission metrics for rotorcraft is estimating the amount of NO_x produced. While there is a large amount of published turbofan NO_x emissions data and established methods for estimating variation with altitude, much of the data for the turboshaft engines used by existing rotorcraft are proprietary. Hence, there is little publicly available data that quantifies NO_x emissions for specific turboshaft engines. There is a limited amount of data that have been collected by the Swiss Federal Office of Civil Aviation as part of their efforts to develop an emissions inventory for civil aviation (Rindlisbacher, 2009). Russell and Basset (2015) generated estimates of NO_x emission rates by assuming that turboshaft and turbofan engines produce similar amounts of pollutants, and used publicly available ICAO turbofan emissions data.

It is also possible to integrate higher fidelity calculations of NO_x generation into rotorcraft sizing codes. Fakhre *et al.* (2014) predicted NO_x emissions using a stirred reactor

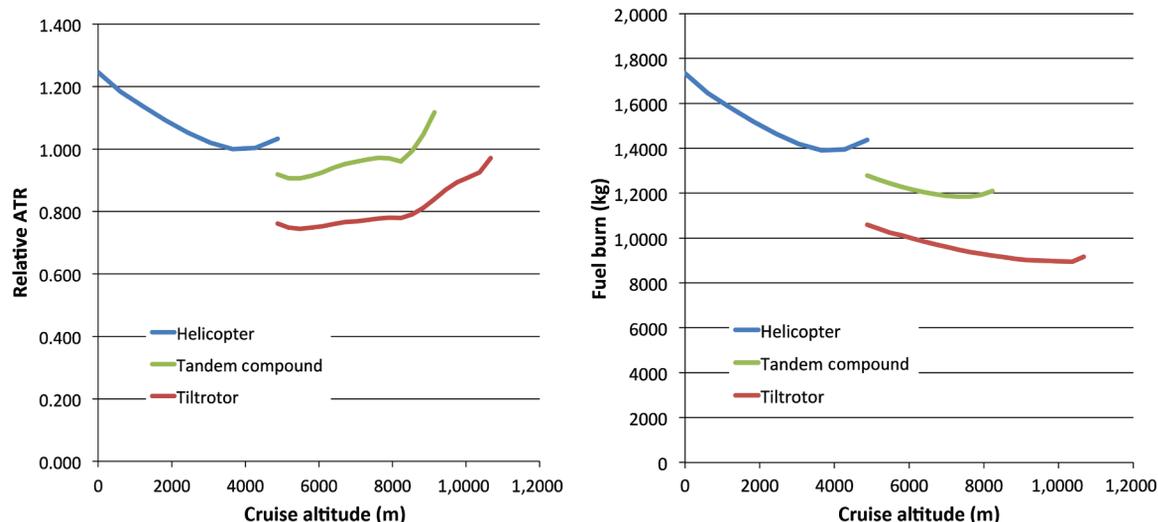


Figure 7. Impact of cruise altitude on environmental impact (ATR), fuel burn, and empty weight. (Reproduced from NASA.)

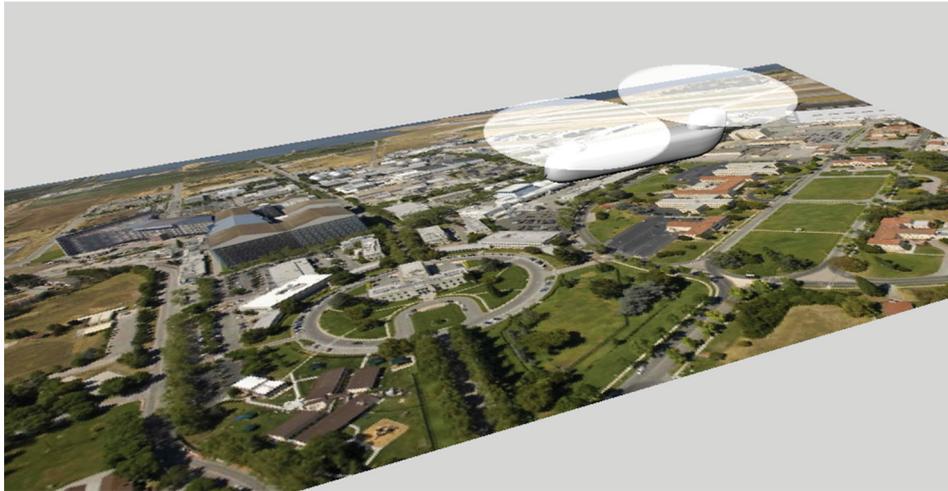


Figure 8. The Hopper concept: an aerial public transit system using rotorcraft. (Reproduced from NASA.)

concept along with a set of simplified chemical reactions. This NO_x estimation capability was integrated with a rotorcraft design and optimization framework, and engine parameters were varied to achieve minimum fuel burn, NO_x , and rotorcraft weight.

4.3 Green VTOL Transportation System: Hopper

There are substantial future challenges related to sustaining and improving efficient, cost-effective, and environment-friendly transportation options for urban regions. A recently completed study by NASA and Stanford University investigated the feasibility of a rotorcraft solution for future urban transportation (Melton *et al.*, 2014; Sinsay *et al.*, 2012). Such an aerial transportation system could ideally tackle concerns related to urbanization, transportation gridlock, and fossil fuel emissions.

The goal of this study was to develop an integrated system simulation that incorporated models of aircraft, vertiport stations, fleet operations, and airspace management technologies to determine the feasibility of using electric-propulsion, vertical takeoff and landing vehicles called “Hoppers,” shown in Figure 8, to serve a metro–regional transportation system.

An expanded vehicle-sizing design space was examined for rotary wing vehicles incorporating electric propulsion. This design space included not only modeling emerging advanced battery technologies but also hydrogen fuel cell systems and hybrid (turboshaft engine and battery/fuel-cell-driven electric motors) propulsion systems. Additionally, the design space was influenced by insights gained during the study into mission profile requirements, particularly vehicle range requirements (25–100 nmi). The notional

transportation network envisioned for the Hopper concept in the San Francisco Bay Area is shown in Figure 9, and a conceptual drawing of a Hopper vertiport is shown in Figure 10.

Altogether, the study revealed that a midterm (next 15–20 years) solution for electric vertical lift vehicles

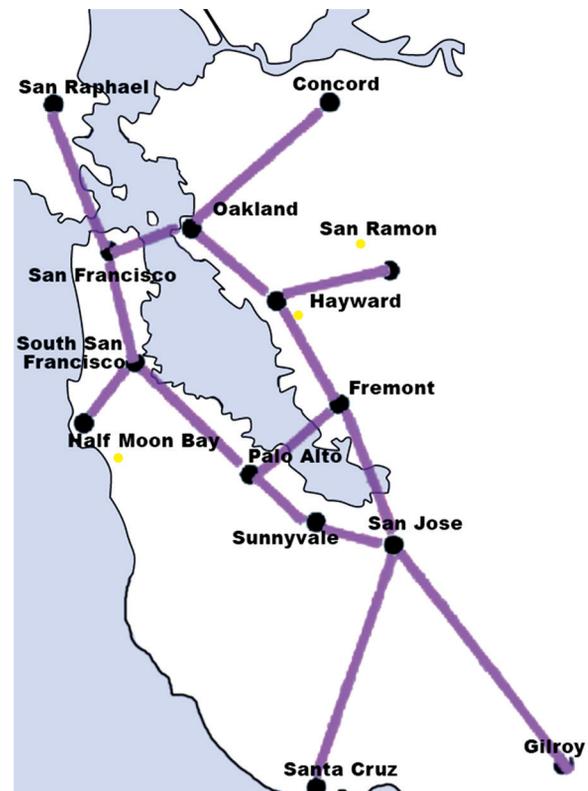


Figure 9. The Hopper Bay Area Network (notionally about 2040). (Reproduced from NASA.)

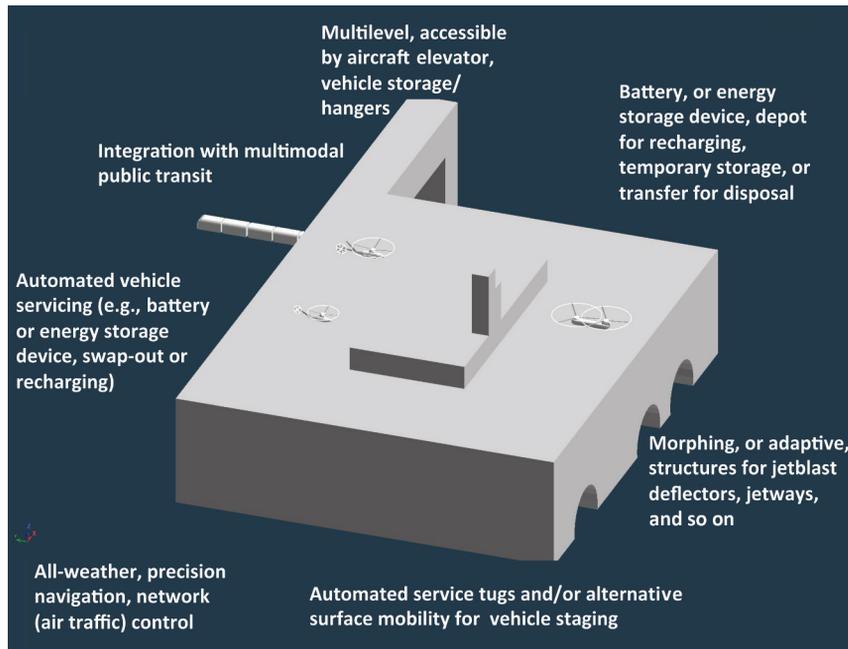


Figure 10. Notional Hopper Station Operations/Capabilities. (Reproduced from NASA.)

supporting the Hopper metro/regional aerial transportation system mission might be feasible. Specifically, relatively near-term battery/hybrid (i.e., turboshaft with battery or fuel cell) technologies can make these short-range vehicles realizable, perhaps within the next 10 years. Near-term battery technology ($500\text{--}600\text{ Wh kg}^{-1}$ at reasonable power densities) will satisfy power and energy requirements for these short-range vehicles.

Other considerations for operating a large fleet of medium- to heavy-vertical-lift vehicles performing sustained frequent overflights in an urban environment include the issues of noise and emissions. From an emissions standpoint, rotorcraft with electric propulsion are more environmentally benign than turboshaft-engined rotorcraft. However, though the vehicles conceptually designed in this study were required to operate at much lower tip speeds and disk loading than conventional helicopters, rotorcraft noise reduction will still be an important technological challenge.

5 SUMMARY

Reducing the environmental footprint of rotorcraft continues to be an active area of research. Noise, emissions, and hybrid/electric powerplants are the main areas being worked on by government agencies, universities, and the private industry. In some cases, green rotorcraft design challenges overlap with fixed wing and automotive research, particularly

in electric motors and energy storage technology. The unique environmental issues associated with rotating wings require continued investment toward greener propulsion systems, and ultimately, greener helicopters.

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