

Realizing the Potential of the Compound Helicopter

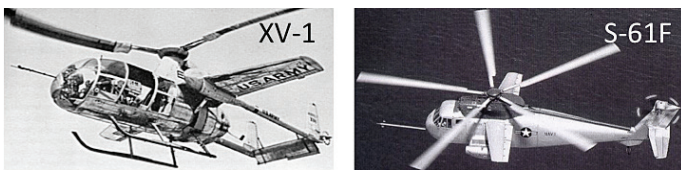
By Robert A. Ormiston

The 2015 Alexander A. Nikolsky Honorary Lecturer summarizes his key findings and recommendations pertaining to the compound helicopter. Full details and references are available in the Nikolsky Lecture published in the January 2016 issue of the *Journal of the AHS*.

In recent years, new interest in the compound helicopter has emerged on several fronts. Indeed, the Sikorsky X2 and Airbus X³ have demonstrated impressive capabilities compared with research compounds flown decades ago. Recent NASA and Army mission design studies have shown that advanced technologies will enable modern compounds to far exceed conventional helicopter performance and even approach tiltrotor performance levels. Under the Army Joint Multi-Role (JMR) Technology Demonstration program, Sikorsky-Boeing and AVX Aircraft are advancing compound technology. And at the AHS 71st Annual Forum in May 2015, Dr. William Lewis, Director of the US Army's Aviation Development Directorate, called for more research on the high-speed winged compound.

Background

The helicopter is the most elegant and efficient of all flying machines in hover and at low speed. However, the inherent constraints of the edgewise lifting, propelling rotor — drag, stall and compressibility — ultimately limit speed and efficiency. In the 1950s and 1960s, compound flight research showed that a rotor could operate and be controlled at high advance ratios. Under the US Army and Air Force Convertiplane Program, the innovative McDonnell XV-1 compound helicopter achieved 177 kt (328 km/h) in 1956. From 1965 to 1969, the Kaman YUH-2A, the Sikorsky S-61F, the Lockheed XH-51A, several versions of the Bell UH-1, and the Piasecki 16H-1A achieved maximum speeds ranging from 195 to 275 kt (361 to 509 km/h).



1950s McDonnell XV-1 and 1960s Sikorsky S-61F research compound.

These successes led to the Army Advanced Aerial Fire Support System (AAFSS) in 1966, with a speed requirement of 220 kt (407 km/h). Lockheed won the competition with the AH-56A Cheyenne and was awarded a production contract for 375 aircraft in 1967. Unfortunately, rotor dynamics problems were encountered and the production contract was cancelled. However, the technical problems were ultimately resolved and the AH-56A met the original performance requirements in 1972.

Nevertheless, the Army abandoned the AAFSS high-speed requirement and adopted the Advanced Attack Helicopter (AAH) mission that led to today's AH-64 Apache. Parallel development of the tiltrotor concept, including resolution of initial challenges with the XV-3, ultimately led to the resounding success of the NASA/Army Bell XV-15 tiltrotor. Following on the heels of the Cheyenne cancellation, this no doubt contributed to the perception that the tiltrotor was the preferred, if not the only, way to achieve an efficient, high-speed rotorcraft. Over the years this view became entrenched as conventional wisdom and the technical community largely abandoned the high-speed compound during a "compound gap" of over three decades.



The relative fortunes of the Army-Lockheed AH-56A Cheyenne compound helicopter and NASA/Army Bell XV-15 tiltrotor contributed to the "compound gap."

Fast forward 30 years to the 21st Century. Strong interest in the compound has reemerged, including the Piasecki X-49 winged compound and the Carter Slowed Rotor/Compound autogyro. Sikorsky revisited the coaxial lift-offset compound and invested in a company-funded X2 Technology Demonstrator that achieved a level-flight speed of 253 kt (469 km/h) in 2010 and won the Collier Trophy. Similarly, Airbus Helicopters (then Eurocopter) developed the X³ company-funded demonstrator and achieved 255 kt (472 km/h) in



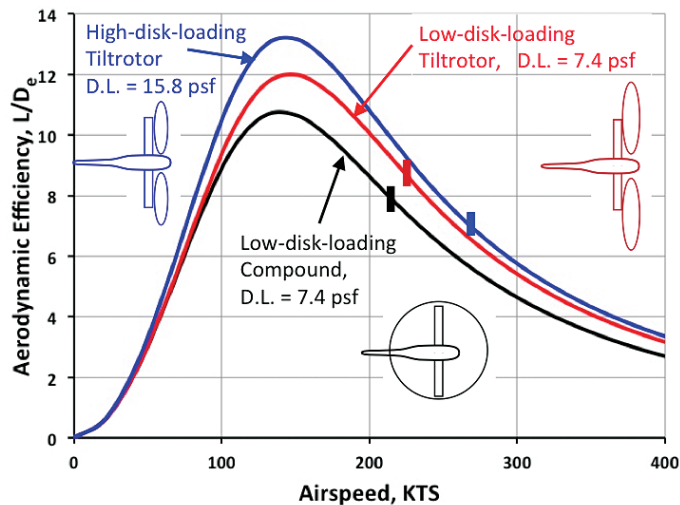
Recent (top) and JMR compounds: Sikorsky X2, Airbus Helicopters X³, Sikorsky-Boeing SB>1 and AVX compound aircraft.

2013. In 2014, the US Army embarked on the JMR technology demonstration program. Sikorsky-Boeing is developing the coaxial lift-offset SB>1 Defiant and AVX Aircraft is developing coaxial compound technology.

So why this renewed interest in the compound? Is it justified? Does the compound make sense after all? Is there a viable role for the intermediate-speed compound in the rotorcraft mission spectrum between the simpler low-speed helicopter and the more complex high-speed tiltrotor? As a start, let's take a look at some numbers.

Performance Potential of the Compound

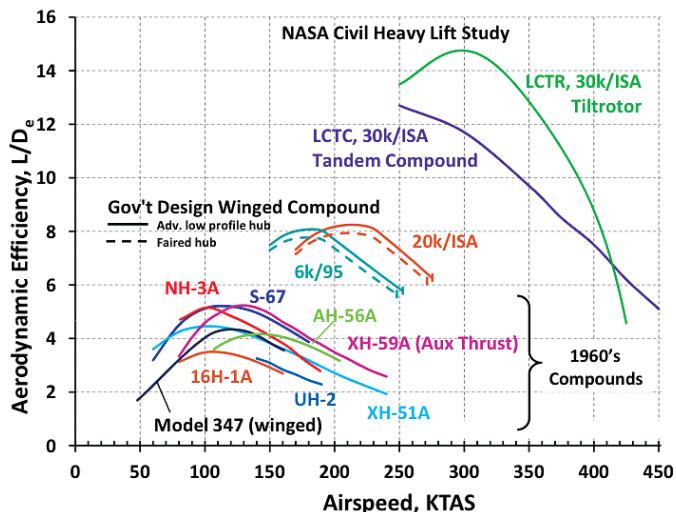
First, consider a simplified analysis comparing the performance of a compound with a tiltrotor having the same low disk loading 7.4 lb/ft^2 ($354 \text{ N/m}^2 \text{ Pa}$), wing span and fuselage drag. The only significant differences are the profile power of the edgewise rotor versus the prop rotor and the rotor hub drag of the compound. It turns out that, with very low drag hub (one-third that of a conventional helo), the maximum L/D_e of the compound is very close to that of the tiltrotor. With the same installed hover power, the maximum speeds (marked in the figure) are 215 kt (398 km/h) and 228 kt (422 km/h) — a difference of only 13 kt (24 km/h)! By increasing the tiltrotor disk loading, the L/D_e increases by shedding the excess proprotor blade area and the maximum speed increases to 270 kt (500 km/h) because of the increased hover power needed with the higher disk loading. Of course, the L/D_e and maximum speed of the compound could be increased the same way. So, we can see that, for the same disk loading, a low-drag compound can be nearly as efficient as the tiltrotor.



Simplified comparison of the performance of a compound helicopter and a tiltrotor.

Similar results may be inferred from numerous NASA and Army mission design studies over the last 10 years for a variety of civil and military mission scenarios based on advanced technology aerodynamics, flight control, structures, materials and propulsion. Overall, both the flight speeds and the L/D_e values for the modern compounds are far higher than the 1960s experimental compounds. Particularly interesting are the tiltrotor and compound aircraft designed for the 2006 NASA civil heavy lift mission for a 120-passenger, 350 kt (650 km/h) cruise, 1,200 nm

(2,200 km) range, short-haul transport. The large civil tiltrotor (LCTR) showed higher L/D_e than the large civil tandem compound (LTC), but the compound showed impressive performance. In another study, an Army winged compound designed for a representative JMR mission showed an L/D_e above 8. Most importantly, the projected performance of the advanced compounds was significantly better than the 1960s experimental compounds.



Comparison of NASA and Army studies.

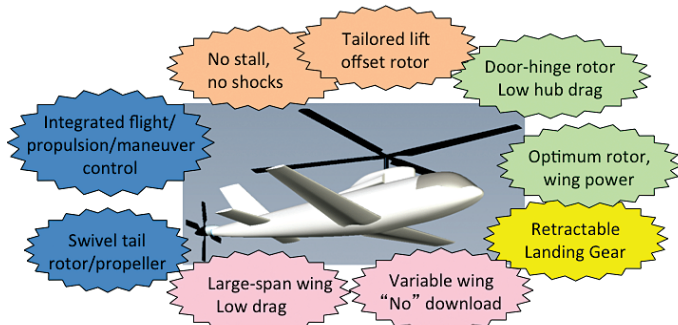
The takeaway from these studies is that, yes, with advanced technology, the compound has the potential for far higher speed, efficiency and performance than the conventional helicopter — and perhaps not far from the tiltrotor — and a modern, simpler, lighter, less complex compound may well have a place for mid-range missions in the rotorcraft spectrum.

Realizing the Potential

To get there we'll need to adopt the most innovative compound configurations, fully exploit materials, structures, propulsion and flight control advances during the years of "compound gap," and vigorously push focused research and development (R&D) in critical technology areas.

For the reimagined compound, it will be necessary to develop and incorporate many, if not all, of the following features and technologies:

- an auxiliary wing comparable in span to the rotor will be needed for high cruise efficiency; variable incidence will minimize hover download for high hover efficiency (an added benefit is optional field removal to maximize payload for low-speed missions)
- the rotor must be slowed significantly to minimize rotor profile power
- the fuselage must be designed for minimum drag and, especially, new technology will be needed to reduce hub drag
- a swiveling auxiliary propeller will provide propulsive force and hover anti-torque and yaw control
- fully integrated flight control technology will be essential to optimize aerodynamic performance and provide control, maneuverability and agility while ensuring flutter suppression and structural load control



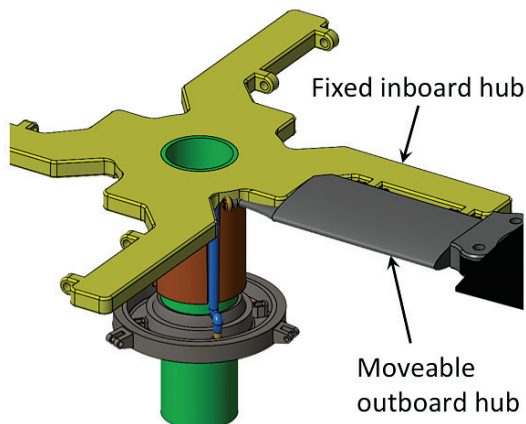
Technologies and features needed for the reimagined compound.

Research Needs — Critical Technologies

Most importantly, if a practical compound with truly high aerodynamic efficiency is ever to be realized, renewed R&D will be essential. The most cost-effective way is to focus and target the key critical component technologies in a step-by-step building block fashion *and we know what these are.*

The primary obstacle to a practical compound helicopter is poor aerodynamic efficiency. To achieve desired mission performance — e.g., approaching the tiltrotor — requires aggressive research to reduce drag: fuselage drag, rotor drag and hub drag. All three are important, so the benefit of reducing one component will be lost if the others are neglected.

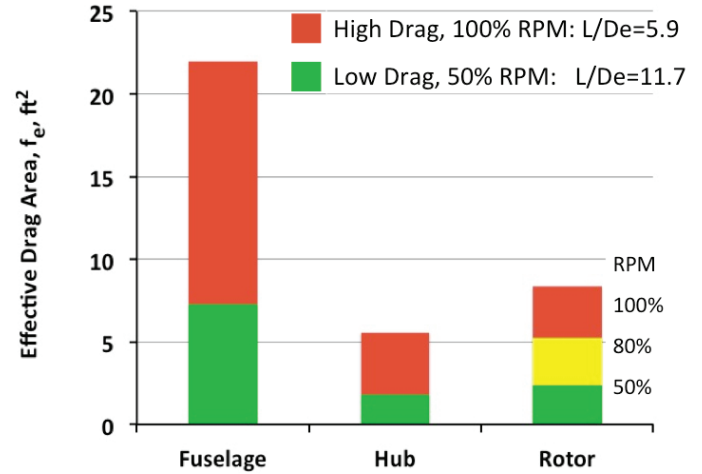
Low Drag Hub: For a truly efficient compound, the drag of the hub is the greatest challenge. It should be reduced to one-third of current modern hubs and this will require innovative and aggressive R&D. Fortuitously, it is easier to reduce hub drag for a compound than for a conventional helicopter because at high speed, the compound rotor operates at near-zero angle of attack and collective pitch. This enables the hub to align with the free-stream flow direction and minimize drag. A door-hinge hub, like the AH-56A stiff-in-plane hingeless rotor, is well suited for low-drag as well as the structural and aeroelastic requirements at high speeds.



Schematic door-hinge rotor hub.

The schematic diagram illustrates one possible configuration. The hub frontal area is reduced to the minimum necessary for the structural members; these are shaped roughly as flat plates — a fixed plate attached to the rotor shaft and hinged to a moveable plate attached to the blade (note that the diagram does not depict shaping that would minimize aerodynamic drag). In cruise flight the

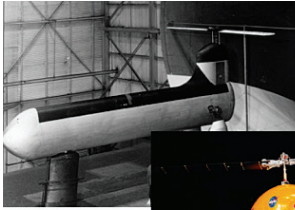
two hub plates would align with the free-stream velocity to minimize drag. Nesting the pushrods and pitch links against the rotor shaft and hub plates reduces frontal area to a minimum in cruise. In hover and low speeds with high collective pitch, when the hub plates would not be aligned, the pitch links would be exposed and the hub drag would increase, but this would be of little consequence at low speeds.



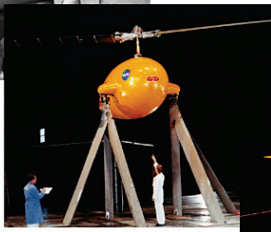
Comparison of rotor drag with fuselage and hub drag and the effect of RPM on aerodynamic efficiency, L/D_e .

Low Drag Rotor: Drag from the rotor blades also needs to be reduced to a minimum. The most effective way is to slow the rotor RPM as shown in the bar chart. Here the drag components from the fuselage and rotor hub are included for comparison. The drag is shown in terms of the customary effective drag area, f_e , for a vehicle of approximately 17,000 lb (7,700 kg) gross weight. The high and low values for the fuselage and hub drag components represent typical current and advanced low drag technology, respectively. Since the rotor f_e is a function of flight speed, the value for the maximum L/D_e condition is shown. It can be seen that the rotor drag can be reduced by about two-thirds by reducing the rotor speed by 50%. Taken together, the slowed rotor with a low-drag fuselage and hub essentially doubles the L/D_e of a compound helicopter, from 5.9 to 11.7. In addition to slowing the rotor speed, it will also be necessary to develop new airfoils to minimize blade drag in the expanded reverse flow region at high advance ratio.

Large-scale Research Rotor Testing: To properly develop optimum compound rotors subject to real-world structural and aeroelastic requirements, a modern large-scale research rotor will be invaluable. Accurate data at advance ratios of 2.0 and above is essential to validate prediction codes and to support compound rotor design. A large-scale wind tunnel offers the best and most cost-effective way to acquire high-quality data, by controlling test conditions and providing sophisticated rotor balance, blade instrumentation and flowfield diagnostic measurements. A large-scale rotor ensures representative structural characteristics, Reynolds number and Mach number. In the 1960s, NASA and the Army tested three full-scale, high advance ratio rotors in NASA wind tunnels and this visionary research needs to be resumed.



Jenkins, 1965
NASA Langley 30-by 60-ft WT
 $\mu = 1.45$



UH-1, 1968
NASA Ames 40-by 80-ft WT
 $\mu = 1.1$



H-34, 1968
NASA Ames 40-by 80-ft WT
 $\mu = 1.1$

Full-scale research rotor testing.

Integrated Flight Control Technology: To achieve the full mission potential of the compound, flight control integration must expand to embrace performance, loads and propulsion. The proper trim angle of attack and collective pitch for optimum aerodynamic efficiency must be maintained — while also “managing” vehicle structural loads, vibration and aeroelastic stability. These are demanding requirements, but they should be attainable with current flight control technology and not require new breakthroughs.

Reducing Risk: History has repeatedly shown that dynamics and aeroelasticity are key risk areas for advanced rotorcraft development. Research is needed to determine how far the rotor RPM can be slowed for the lowest possible rotor drag before the constraints of control response, dynamics and blade aeroelasticity are reached. It is essential to avoid aeroelastic surprises. Inexpensive small-scale models can be used to explore the limits of high advance ratio operation and validate analysis methods.

Innovative Low-cost Flight Research: Finally, unmanned aerial vehicle technologies embodied in the ubiquitous multi-copters and drones now used by hobbyists, universities and

small companies are opening new opportunities for rotorcraft R&D. Exploration of compound rotorcraft aeromechanics including vehicle trim, steady and maneuver rotor loads, and flight control integration should be pursued using small low-cost vehicles to complement and augment traditional analytical, laboratory, wind tunnel and full-scale flight test methods.

The Path Forward

Having settled questions not asked during the compound gap and having arrived at successful solutions for the key component technology challenges, the stage will be set for an optimized and cost-effective “clean sheet of paper” design of a truly successful and convincing full-scale compound technology demonstrator.

Compound helicopter R&D has been neglected far too long. Recent flight demonstrators and design studies show that a modern winged compound would be a viable candidate for missions between the simpler low-speed helicopter and the more complex high-speed tiltrotor. It is time to vigorously pursue this opportunity with targeted R&D to unleash the potential of the compound. If the technical community steps up now with foresight, vision, and strong government and industry leadership, the compound is almost certainly assured a bright future.

About the Author

Dr. Bob Ormiston was the 2015 Alexander A. Nikolsky Lecturer; this article excerpts and summarizes portions of his lecture, “Revitalizing Advanced Rotorcraft Research — and the Compound Helicopter,” which was published in the *Journal of the AHS*, January 2016. This and all of the available Nikolsky Lecture articles and presentations can also be found at www.vtol.org/nikolsky. Ormiston retired in 2014 as the US Army’s Aeromechanics Chief Scientist. He remains an Emeritus Scientist at the Army Aviation Development Directorate — Aeroflightdynamics Directorate (AFDD) at Moffett Field, California.



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