Is there a Case for the Tiltrotor?

by **Dr J. Gordon Leishman**

Gordon Leishman is the Minta Martin Professor of Engineering at the University of Maryland and the proprietor of Rotor Systems Research, LLC, an aerospace consulting firm. Here he takes an objective look at some of the performance capabilities of the tiltrotor versus the present and potential future capabilities of the helicopter. This article contains extracts from his second book The Helicopter: Thinking Forward, Looking Back, *which is reviewed elsewhere in this edition.*

Modern militaries have frequently argued for higher-speed aircraft in order to perform their missions more effectively. But for any aircraft, there is always a much higher cost for better speed, as well as other trade-offs in performance, such as range, payload or flight endurance. Combining higher speed with a pure vertical takeoff and landing capability can provide unique transport (and other) capabilities, but at an even higher cost. This cost appears in terms of the technology development, as well as in the manufacture and eventual operation of the aircraft, but clearly any aircraft that removes or otherwise limits a dependency on concrete runways gives any operator, military or civil, an unparalleled operational capability and flexibility.

The conventional helicopter has traditionally filled this vertical lift transport role. While the helicopter has a plethora of civilian uses, without doubt the modern military would simply fail to function efficaciously without access to its unique capabilities. But while the helicopter is a remarkable rotating-wing aircraft and a triumph of modern aeronautical engineering, it is also a technically compromised aircraft, with several performance limitations including its range and maximum cruise speed. For example, Figure 1 gives historical trends that show that it has taken over half a century of technical development to bring the best cruise speeds of modern helicopters up to only about 150–165 knots. The casual observer could easily be forgiven for being unimpressed by such relatively low speeds!

An Alternative to the Helicopter?

The engineering community has long recognised the various performance issues with the helicopter, and particularly the unique technical difficulties and challenges in improving upon its cruise speed. The helicopter has probably not yet reached the limits of its performance potential, but improving further upon its existing capabilities will require more innovative technologies than have been used thus far.[1] For over five decades, the rotorcraft industry has also pursued alternative concepts in an attempt to combine the unmatched hovering efficiency of a helicopter with the much higher cruise speeds that are possible with an airplane. The tiltrotor is one such 'hybrid' or 'convertible' rotor concept, although other concepts such as tiltwings have also been proposed.[2] By their design, tiltrotors can cruise significantly faster than helicopters, and so offer at least one major performance advantage. The tiltrotor has a 50-year history of development,[3] from the Bell XV-3 (first flown in 1955) to the Bell–Boeing V-22 Osprey. But like the helicopter, the tiltrotor is also a compromised engineering design (perhaps even more so), and it is not as aerodynamically efficient as a helicopter in hovering flight or as efficient as an airplane in forward flight.

For decades the US Marine Corps has argued the effectiveness of the higher-speed tiltrotor concept to replace the helicopter, citing major advantages for its medium lift assault support mission,[4] amongst other reasons. While it has been claimed that the relative speed 'productivity' ratio of a tiltrotor that flies at 300 knots is '57% better' than a helicopter that flies at only 150 knots with a given payload over a 200nm radius of action[5] (Figure 2), this argument discounts other factors that tell a more intricate and revealing story about the performance capabilities and economics of operating a tiltrotor. Least of all, the current incarnation of the tiltrotor (i.e. the V-22 Osprey) has

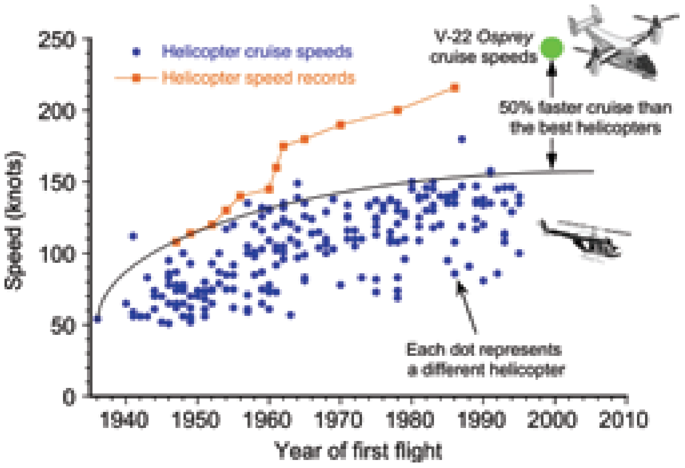

Figure 1: Increase in helicopter cruise speeds

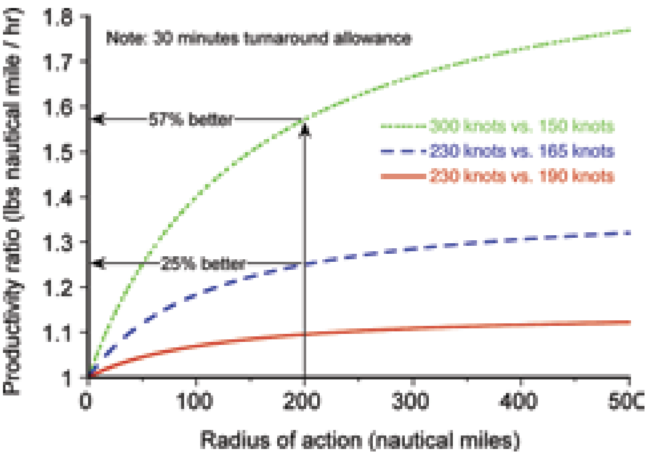

Figure 2: The tiltrotor productivity ratio

demonstrated cruise speeds only in the 220 to 250 knots range[6] (depending on its weight and operational altitude), which is only about 35–50% faster than is possible with modern helicopters, and is certainly not 'twice as fast' as has been superciliously claimed.[7] The data in Figure 2 show that the productivity ratio of the tiltrotor at this speed only gives a gain of 25% over the helicopter at 200 nautical miles. Technology developments already in the pipeline mean that future helicopters will likely cruise at speeds approaching 190 knots,[8] and on this basis only a 9% increase in speed productivity would be obtained over the helicopter.

The conventional helicopter has traditionally filled the vertical-lift transport role

Productivity in Terms of Efficiency

But cruise speed is not the only metric for measuring the transport utility of any type of aircraft – what is fundamentally important to an operator (military or civil) is payload and range, as well as transportation *efficiency* (i.e. benefit versus cost). Aircraft design requirements are usually based on the ability to carry a certain payload over a specified range or radius of action. For a rotorcraft concept, a hover time and/or a cruise speed requirement will also be specified, which results in trade-offs between efficient hovering-flight and/or low-speed flight performance (e.g. flight endurance, maximum external load carriage, etc.) against efficient cruise performance (e.g. range, cruise speed, maximum speed, etc.). Significantly, the results in Figure 3 show that the tiltrotor can carry only about half the payload of a transport helicopter such as the Sikorsky CH-53E, and to *any* range.[9] Figure 3 also shows that the payload of the tiltrotor is eroded considerably when it must take off vertically at higher density altitudes, and this loss of performance capability is worse than for a conventional helicopter. In fact, at 'hot and high' conditions the tiltrotor is significantly outperformed, in terms of both payload and range, by even medium-weight utility helicopters such as the UH-60 Blackhawk[10]. Yes, the tiltrotor has its niche with its higher cruise speed, but as a load carrier it certainly does not jump out as an outright replacement for the helicopter.

The tiltrotor has an even more limited useful payload capability when carrying a payload to longer ranges because, like the helicopter, it is not as aerodynamically efficient as an airplane, and so it has to carry a great deal of fuel to fly to these longer distances. In fact, the V-22 Osprey has demonstrated a maximum internal payload carriage of about 10,000lbs to a range of about 500 nautical miles at sea-level conditions. This is only moderately better than many so-called 'legacy' helicopters, and inferior to some modern helicopters.

Figure 4 shows a summary of the trade-offs between maximum payload and maximum range for many different helicopters. A helicopter can be designed to carry a significant useful load over short distances by trading against fuel capacity, or can carry a smaller payload over ranges of maybe up to 1000nm by using long-range fuel tanks. Greater ranges are possible, but both the size of the aircraft (which drives both empty weight and costs) and the amount of fuel that must

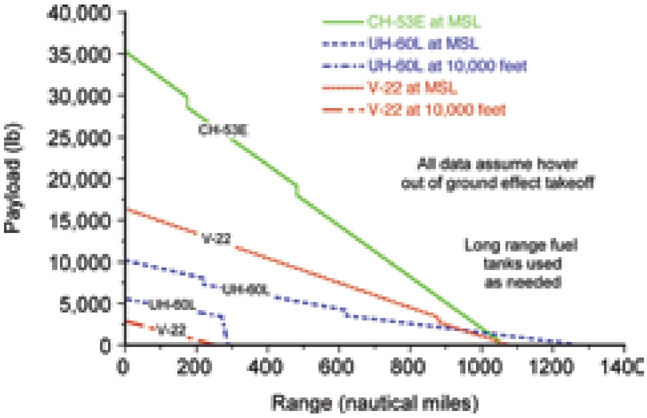

Figure 3: Productivity ratios of tiltrotor and helicopters

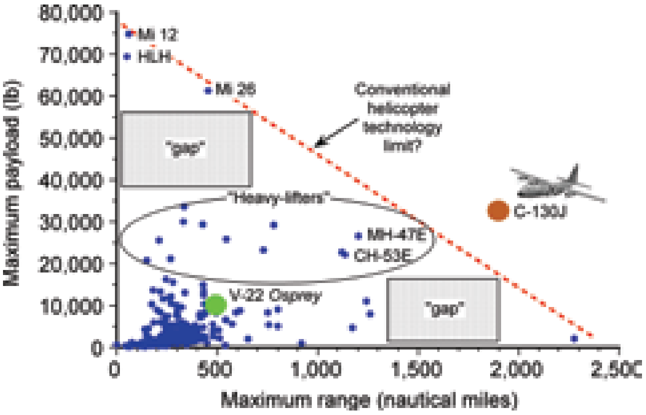

Figure 4: Payload versus range

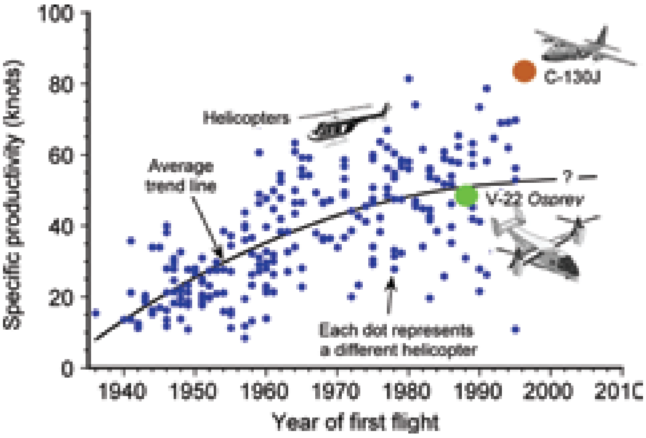

Figure 5: Specific productivity

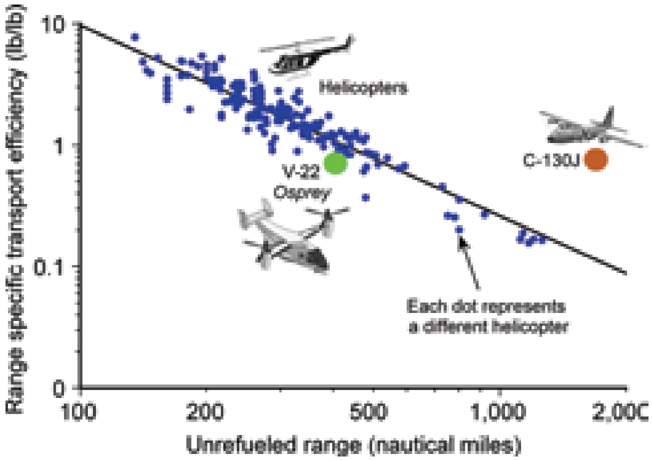

Figure 6: Range specific transport efficiency

be carried to meet that range erode its payload as a fraction of its total weight. When viewed on this basis, the tiltrotor does not provide any enhanced payload or range capabilities over that possible with the conventional helicopter. Perhaps more significantly, Figure 4 shows that there are big gaps in overall vertical-lift capabilities. This is not to say that such capabilities are needed, at least for now, but certainly a tiltrotor in the form of the V-22 Osprey provides no further capability in these regions of the vertical-lift spectrum.

Productivity as Value Delivered per Resource Expended

A more relevant measure of 'productivity' for an aircraft must be viewed as value delivered per critical resource expended. The idea of such a metric is to give a useful measure of an aircraft's economic performance – the cost per seat mile for an airliner is a good example. One such metric is *specific productivity,* which is defined as the product of the maximum payload transported (over a given distance) and the speed of transportation, normalised by the maximum takeoff weight of the aircraft. It factors in the effect that while larger aircraft may carry more payload (albeit not always at greater speed), they are usually also more expensive to own and operate.

The trends in Figure 5 detail specific productivity data in terms of a 200nm stage distance (trading payload for fuel to reach that range). The trends are asymptotic, with little change in over two decades, merely confirming that helicopters are now reaching aerodynamic and other technical barriers limiting their productivity, that are much harder to overcome using current technologies. But the data given in Figure 5 also suggest that the tiltrotor is not the answer to improving vertical-lift productivity. The ability of the V-22 Osprey to cruise up to 50% faster than a modern helicopter is nearly all offset in terms of its specific productivity by both its relatively lower payload capability and its relatively higher empty weight (i.e. poorer structural weight fraction[11]) compared to a helicopter.

Continuing further the productivity argument, the *range specific transport efficiency* can be defined as the ratio of the payload weight transported to the fuel weight consumed for a specific transport range (Figure 6). This quantity is similar to the specific productivity index used in Figure 5, but the transport efficiency calculation allows the effectiveness of different aircraft designs (i.e. helicopters versus tiltrotors versus airplanes) to be more objectively compared, because it is a better measure of unit payload transported per unit of resource expended. It is interesting to see from the data in Figure 6 the strong correlation for a wide variety of helicopter types (note the logarithmic scale). Clearly, at longer flight ranges the helicopter becomes a much less productive aircraft concept. This is because of its relatively low aerodynamic efficiency in forward flight (less than a third of the cruise efficiency of an airplane) and the need for it to carry a great amount of fuel to reach these longer ranges.

Also of significance is that current tiltrotors do not exceed the capabilities of the helicopter for the typical transportation missions that the helicopter already performs well. In fact, these results show that both the specific productivity *and* the transport efficiency of the V-22 Osprey are no better than a helicopter's, even with the Osprey's cruise speed advantage of more than 70 knots[12]. But extrapolating the trend line shown in Figure 6 suggests that neither the helicopter nor the tiltrotor could be as productive as a load carrier compared to the airplane at longer ranges, even if one big enough and capable enough to carry the necessary amounts of fuel could ever be built!

The Real Cost of a Tiltrotor

The specific transport efficiency metric takes 'cost' into account on the basis of equal cost per unit weight of aircraft. Actual costs of the V-22 Osprey provide another benchmark to address the transport productivity of a tiltrotor concept relative to a helicopter in terms of payload transported per cost of resource expended. While some would say that the military services are not running an airline (and the airlines are currently not flying tiltrotors), the economic viability of any aircraft to any operator still ultimately centres on costs. The Osprey programme has cost in excess of $15Bn as of 2006, and acquisition costs[13] for each Osprey are now cited at over $96M in FY2004, while the FY2005 US defence budget quotes nearly $115M per aircraft, excluding development costs. Based on empty weight, this is several times the cost of an average medium-weight military helicopter[14], and several more times the cost of a military transport airplane. Factoring in the higher operating costs of a tiltrotor can only make such a comparison even more revealing – the tiltrotor will always have relatively higher costs because it has mechanical and system elements that are common to both the helicopter and the airplane[15].

Such results do nothing to bolster the case for a tiltrotor over a helicopter, technically, operationally or economically. The evidence suggests that the current incarnation of the tiltrotor, at least as a transporter, cannot compete with helicopters on any *performance* basis except for speed. But speed is where the tiltrotor has its niche, at least for now, although it is a performance niche that becomes hard to justify to an operator if significant compromises in range, payload and productivity are the price to pay, as well as higher capital and operating costs. These issues become even more acute for the tiltrotor when its missions demand extensive hovering flight time (tiltrotors have higher fuel burn compared to helicopters when carrying the same payload), operations at 'hot and high' conditions (see Figure 3), or when payloads have to be transported over relatively short ranges of less than 100nm, where Figure 2 has shown that higher speed never matters.

> *'The current incarnation of the tiltrotor cannot comete with helicopters on any performance basis except for speed'*

The Bell–Boeing V-22 Osprey

Conclusion

The risks in developing any new rotorcraft concepts can be taken only if the performance and economics can both be justified, and they must be justified with respect to the helicopter and the missions the helicopter already performs well. When viewed objectively, the current incarnation of the tiltrotor (the V-22 Osprey) does not make that case, and the aircraft offers limited, if any, transportation improvements over current helicopters. Speed margins between the helicopter and the Osprey are likely to shrink in the near future as helicopters continue to advance in their technology, and new innovations such as flow control begin to make quantum improvements to their performance. But the US Marine Corps clings to the view that the tiltrotor by itself is vital to its future operations, and that even modern helicopters will just not do the missions that it demands. But it has been a very long wait, and after two decades of development and testing the Osprey is only now about to enter operational service[16].

The development of a tiltrotor must certainly be viewed as a significant technical accomplishment for the rotorcraft industry. But so far the tiltrotor as a concept has fallen short on demonstrated levels of performance compared to a helicopter, and its real costs have risen to quite unprecedented levels. Unfortunately, the V-22 Osprey now appears to have become an aircraft that is more at the centre of politics and emotions rather than at the forefront of modern rotorcraft engineering. While the tiltrotor as a concept may still have a future role to play in the vertical-lift aircraft spectrum, replacing the modern helicopter outright with the tiltrotor (at least in its current incarnation) for the missions the helicopter already does well, seems a flawed strategy. A more effective strategy may well be to augment overall vertical transport capabilities with a mix of both tiltrotors and modern helicopters. Perhaps only time will tell, but the ultimate success of any future tiltrotor concepts, military or civil, American or European, will firmly hinge on the demonstrated capabilities of the V-22 Osprey over the helicopter fleet when it finally goes into US military service in late 2007. ■

NOTES

[1] Some of these technologies are already poised to make 'quantum' leaps in helicopter performance. This will include 'active' flow control and 'smart' structures – see: Leishman, J. G., *The Helicopter: Thinking Forward, Looking Back,* College Park Press, College Park, MD, 2007

[2] Rogers, M. J., VTOL *Military Research Aircraft*, Orion Books, New York, NY, 1989

[3] Tiltrotor and tiltwing 'convertible' rotor concepts were also explored in Britain during the 1950s by Raoul Hafner, although a prototype was never flown

[4] As long ago as 1968, the Marine Corps recognised the need to replace its fleet of medium-lift CH-46 and CH-53 helicopters, with an initial deadline of the early 1990s

[5] Gaffey, T., 'Large Cargo Rotorcraft: Bell Helicopter's Perspective', *American Helicopter Society 56th Annual National Forum Proceedings*, Alexandria, VA, 2–4 May 2000

[6] *V-22 Osprey Program – Report on Operational and Live Fire Test and Evaluation, Office of the Director, Operational Test and Evaluation*, The Pentagon, September 2005

[7] As reported on the manufacturer's own website: http://www.textron.com/textron_businesses/bell/bell_helicopter_products.jsp

[8] The speed record for a helicopter is 216 knots, which was set in 1986 by a Westland Lynx.

[9] Committee on Naval Expeditionary Logistics, National Research Council, *Naval Expeditionary Logistics: Enabling Operational Maneuver From the Sea,* Appendix D, National Academies Press, Washington, D.C., 1999

[10] A UH-60L helicopter can lift (fuel and useful load) over 5,600lbs at a takeoff altitude of 10,000 feet versus only some 2800lbs of equivalent load for the V-22 Osprey. The UH-60L can also carry 3000lbs of useful load at this altitude to some 250 nautical miles, a feat unmatched by the V-22

[11] Defined as the ratio of the empty weight to the maximum gross takeoff weight of the aircraft

[12] The conventional helicopter has not reached the limits of its potential, and projections are that the cruise speed differential between the V-22 Osprey and modern helicopters will quickly shrink in the future

[13] Based on official US Government budgetary data

[14] Harris, F. D., and Scully, M. P., 'Rotorcraft Cost Too Much', *Journal of the American Helicopter Society*, Vol. 43, No. 1, January 1998, pages 3–13

[15] Perhaps to reinforce this point, the reported reliability of the Osprey has not yet shown better levels of mission readiness over the 'legacy' helicopters that it may replace

[16] The V-22 was originally forecast to enter service over 15 years ago in 1991