Aerodynamic Limits on Large Civil Tiltrotor Sizing and Efficiency

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Summary

The NASA Large Civil Tiltrotor (2nd generation, or LCTR2) has been the reference design for a variety of NASA studies of design optimization, engine and gearbox technology, handling qualities, and other areas, with contributions from NASA Ames, Glenn and Langley Centers, plus academic and industry studies. Ongoing work includes airfoil design, 3D blade optimization, engine technology studies, and wing/rotor aerodynamic interference. The proposed paper will bring the design up to date with the latest results of such studies, then explore the limits of what aerodynamic improvements might hope to accomplish. The purpose is two-fold: 1) determine where future technology studies might have the greatest payoff, and 2) establish a stronger basis of comparison for studies of other vehicle configurations and missions.

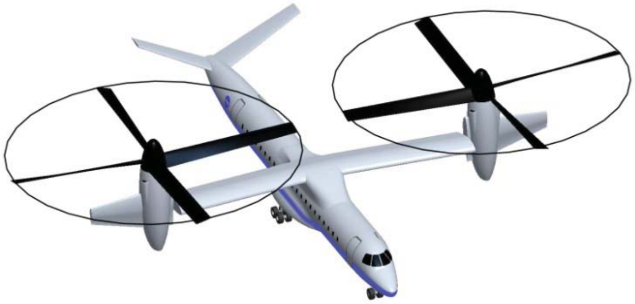

Fig. 1. The NASA Large Civil Tiltrotor, LCTR2 baseline version.

Figure 1 shows the baseline LCTR2, described in detail in Ref. 1. The LCTR2 design goal is to carry 90 passengers for 1000 nm at 300 knots, with vertical takeoff and landing. The larger purpose of the NASA design is to provide a consistent basis for evaluating the benefits of advanced technology for large tiltrotors. This issue is of increasing importance as rotorcraft designs begin to evolve into more exotic concepts, or at least unfamiliar ones, and begin to incorporate hybrid propulsion technologies; traditional design rules of thumb may no longer apply.

Technical Discussion

For the LCTR2, aerodynamic optimization proceeds in three broad steps: (1) the isolated rotor, at a fixed sized, is optimized with CFD in axial flow; (2) the optimized rotor is combined with a wing, and the performance, including aerodynamic interference and non-axial flow, is determined with an aeromechanics code; and (3) the rotor performance so determined is input into a sizing code, which optimizes the total aircraft design. For the present work, the CFD code is FUN3D (Ref. 2), the aeromechanics code is CAMRAD II (Refs.3 and 4), and the sizing code is NDARC (Refs. 5 and 6). In parallel with aerodynamic optimization, structural and engine models were also developed for incorporation into NDARC (Refs. 7 and 8).

NDARC is a convenient tool for exploring the limits of achievable efficiency. The examples given in this abstract are based on the concept of an "ideal" rotor with figure of merit (FM) and propulsive efficiency (η) both equal to unity. FM and η may be further broken down into induced and profile power components. Induced power can be represented by the induced velocity factor K_i, where from momentum theory K_i=1 is the minimum possible induced velocity, hence minimum possible induced power. Profile power results from profile drag c_{do}, where the minimum value is zero. NDARC can set either K_i or c_{do} to their minimum values for hover and cruise separately. Similar analyses can be performed for the wing, where hover download, profile drag, and induced drag can be separately set to their minimum values.

Figure 2 summarizes the results of applying different combinations of ideal wing and rotor performance to LCTR2 sizing. Weight empty, mission fuel burn, and installed power are all plotted as percentages of the baseline values; the lower limits are adjusted to best reveal the effects of different component improvements. "Ideal Cruise" applies K_i=1, c_{do} =0, or both to cruise conditions only; "Ideal Hover" applies to hover only. The "FM, η" bars include ideal values of both K_i and c_{do}, hence FM=1 and η=1 simultaneously. Similar plots are shown for the wing, where the "Ideal Wing" bars include minimum values of download, induced drag and profile drag simultaneously. The plotted results are deliberately unrealistic, in that they represent the extremes of what is physically possible. Further improvement will require changes to the LCTR2 configuration itself.

Scanning across the columns immediately reveals the changes with the largest improvements in each category (weight, fuel or power). Improvements to rotor performance almost always have a greater effect than improvements to the wing.

The single largest improvement in all categories results from a reduction in rotor induced power (K_i) in hover. This implies that LCTR2 cruise performance might be usefully traded off against hover performance. It is not surprising that reductions in profile drag (c_{do}), for either the rotor or the wing, yield the next largest improvement, seen as a decrease in fuel consumption. A very large reduction in engine size is theoretically achievable. Note that this applies to any type of propulsion system and represents the limit imposed by the aerodynamics of the vehicle, not the thermodynamics (or electrodynamics) of the engine. Reductions in empty weight are limited by the fixed fuselage size needed to carry 90 passengers, hence one would expect to see relatively larger reductions in engine size and fuel consumption.

However, Fig. 2 does not tell the whole story. The LCTR2 is required to have enough reserve performance to achieve a 45-deg banked turn at 80 knots (5k ISA+20°C, 90% MCP conditions). This requirement sets the maximum allowable blade loading $C_{T\mathrm{max}}/\sigma$ (it is in effect a stall limit; see Ref. 9). There is no well-defined ideal for stall corresponding to the momentum theory limits of FM=1 or η=1, so there is no direct comparison to Fig. 2. However, if one applies the same percentage reduction to K_i (strictly, $1+\Delta(K_i-1)$) and c_{do}, and a corresponding increase to $C_{T\mathrm{max}}/\sigma$, the largest improvement to overall vehicle efficiency results from higher blade loading, not higher rotor or wing efficiency (at least not as traditionally measured; see Ref. 10 for a different view of the matter). This leads to the paradox that maximizing rotor and wing efficiency may not result in the most efficient aircraft.

These and other results will be presented in more detail in the full paper, with further discussion of the possible pitfalls of component optimization too narrowly applied, and with discussion of appropriate requirements for multi-component, multi-condition optimization needed for practical VTOL aircraft designs.

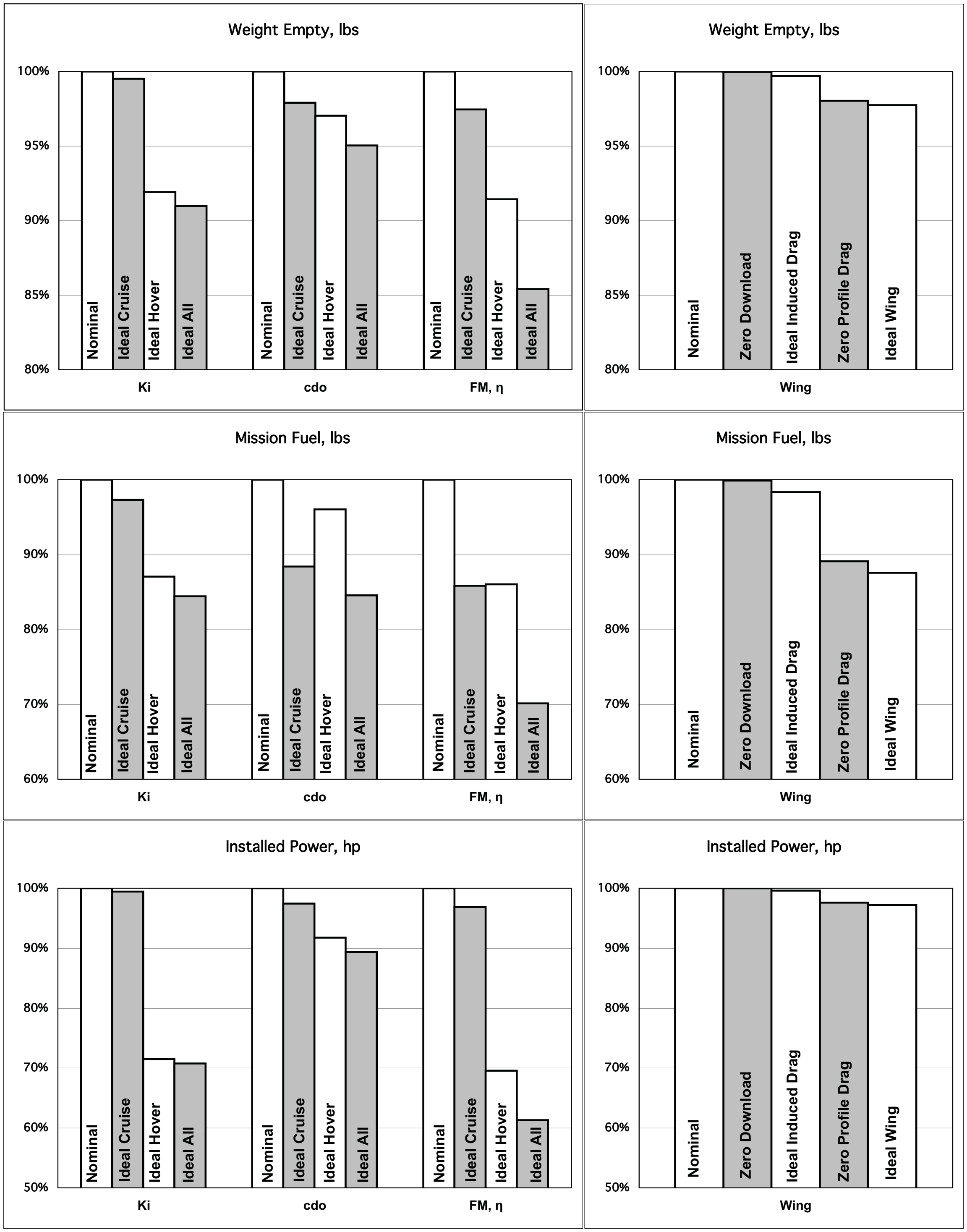

Fig. 2. Impact of ideal rotor and wing performance on LCTR2 design. Ideal rotor performance is shown on the left as K_i, c_{do}, and FM, η; ideal wing performance is shown on the right.

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