Design and aerodynamic considerations about the civil VTOL aircraft Ray

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ABSTRACT

The Ray design consists of a fan-in-wing aircraft specialized as a quadrocopter enhanced with a pair of tilt-ducts at the stabilator. We explain how the civil needs influence the design. To keep operational costs acceptable, the installed power needs to be kept in a moderate range. To reduce the power need in hover flight the wing-fans have a low disc loading. The big fans lead to a low wing loading and high Reynolds numbers in fast cruise flight. These special conditions lead to a wing layout with a big wing area and small aspect ratio. This unorthodox wing layout is discussed and evaluated for the cruise flight. We conclude that the chosen small aspect ratio is optimal for the Ray design. For the critical transition phase we focus on the interaction of the wing-fans with the wings and the tilt-ducts. Fan-in-wing designs have a tendency for additional pitch up moments in the transition. With the tilt-ducts placed behind the center of gravity we can control the pitch in hover, transition and cruise flight. They perfectly fit the need for a controlled pitch down moment to counter the pitch up tendency of the fan-in-wing arrangement in transition.

NOTATION

AOA	Angle Of Attack
AR	Aspect Ratio
CFD	Computational Fluid Dynamics
CG	Center of Gravity
MTOW	Maximum Take Off Weight
VTOL	Vertical Take Off and Landing

INTRODUCTION

Vertical takeoff and landing (VTOL) designs with the same cross section of accelerated air for hover and cruise are either inefficient in hover or in cruise.[1] This leads to high power need or bad performance of all known VTOL aircraft with the same propulsion system for hover and cruise.

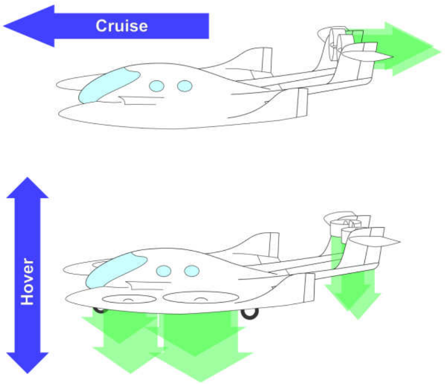

Figure 1. Drawings of the Ray in hover and cruise mode

VTOL designs with separate or additional propulsion systems to generate lift for the hover phase, have to carry extra weight as unused ballast in cruise mode. This extra weight leads to an increase in induced drag. The higher the cruise speed and the lower the wing loading of a design, the less this extra weight has impact on the cruise efficiency.

The Ray design uses wing-fans to create the lift for hover. It is a fan-in-wing design specialized as a quadrocopter and enhanced with tilt-ducts at the stabilator. Each wing encases 2 relatively big fans arranged behind each other, which leads to an exceptional deep wing and a low wing loading. The Ray has further improvements for control, security, economy and performance not discussed in detail in this paper.

When compared to historical VTOL designs[2], the Ray design is an improved Vanguard Omniplane (or GE-Ryan XV-5A) combined with the successful transition control of the Bell X-22A.

Fan-in-wing designs enclose all hover components in an aerodynamic way in cruise flight and therefore are likely to fulfill the promise for an efficient cruise flight. The historical fan-in-wing designs showed more trouble in hover and transition.

The Vanguard Omniplane (and the XV-5A) had only 2 smaller fans in the middle of the wings. The small fans lead to high disc loading and thus to a high power need for vertical takeoff. The engineers substantially increased the engine sizes, but still didn't seem to have reached enough

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lift and control for vertical takeoff. The added nose fan leads to better control, but obstructs the pilot's view for vertical landing. For hover flight the center of the lift of all fans must match the center of gravity (CG). In classic aircraft design the CG is placed at the quarter line of the wing. To fulfill this rule the fans should be placed more to the front or the nose fan has to carry a substantial part of the aircraft weight. If the wing-fans are placed more to the front, their size would have to be reduced which leads to a further increase of power need. The alternative would be to increase the wing depth without increasing the fan size and keeping the fan in a forward position. On the other hand, wing-fans in a forward speed regime (in transition) have only a good efficiency if placed close to the trailing edge of the wing[3]. This leads to the conflicting demands to place the fan either more to the front (for hover lift) or completely to the back (for lift efficiency in transition).

With two fans in a row (one in front and another close to the trailing edge) the Ray design can solve this conflict by adjusting the power distribution depending on the current need.

Further, fan-in-wing designs (especially the GE-Ryan XV-5A as the only full scale flying example) showed difficulties in controlling the transition phase[6] [7] [8]. As discussed in the chapter "EFFECTS OF USING TILT-DUCTS IN COMBINATION WITH FAN-IN-WING" those difficulties probably arose from pitch-up tendencies. A blowing down nose fan isn't much help to counter pitch-up tendencies. A thrust vectoring device in the back on the other hand is a very powerful way to control pitch-up moments.

The Bell X-22A is a very positive example in the history of VTOL aircraft design as it showed very reliable transition control. Due to this transition robustness, it was used for many years as VTOL research aircraft, although that concept never lead to a serial production.

The disadvantage of the X-22A was the technical complexity of the power distribution system and that it didn't match the requested efficiency in hover and cruise flight. This might have been from unattainable demands from the US-Marines. From a technical point of view it is again due to the optimization conflict when using the same propulsion system for hover lift and for cruise propulsion[1]. The tilt-ducts were used not only for transition control, but also for 100% of the lift for vertical takeoff and 100% of the thrust for cruise flight. Therefore the sizing and detailed layout of the X-22A ducts was a compromise to deliver very much thrust at zero speed (hover flight) and some thrust at cruise speed. That compromise lead to high power need for takeoff and a cruise performance that didn't meet the request. In a NASA Contractor Report (CR 177619) about the X-22A, Mr. Woodrow L. Crook suggests to use a lower total fan area, hence much higher pressure ratio fans for better cruise efficiency.[9] When using the same small fans to create all the lift for vertical takeoff it would lead to exorbitant power need.

As the Ray design doesn't need a substantial contribution of the tilt-ducts to the lift for vertical takeoff, we can combine the transition control of the X-22A and follow the suggestion of Mr. Crook for efficient cruise propulsion by having smaller tilt-duct diameters than the X-22A.

Technical implications from civil needs

Successful VTOL designs for the military market like the F-35B, the Harrier or the V-22 might be difficult to transform into aircraft for the civil market. This is mainly due to other priorities of the design properties.

Aspects which are more important for civil applications than for military:

- Minimize power need for hover takeoff to limit engine and overall system price
- Limit cruise drag to minimize operational costs per service
- Static stability for easier certification and a simpler to develop fly-by-wire system

Aspects which are less important for civil applications:

- Maximum speed
- Maneuverability
- Maximum service ceiling
- Maximum useful load per size or per unit
- Detectability (radar cross-section, infrared signature, visibility, silent radar)

We concluded to follow these goals:

- Small disc load for hover takeoff - in comparison to other VTOL designs
- Layout for static stability => dihedral wings, horizontal and vertical stabilizers
- Provide optimal control for hover and transition => Quadrocopter + thrust vectoring
- Exiting air of tilting devices shouldn't interfere with the wings or control surfaces
- Accept slower speed, if it enables lower costs per service

We plan to use a non-pressurized cabin to save weight. This helps to reduce power need and thus costs. The disadvantage of a non-pressurized cabin is a slower cruise speed. The Ray concept would profit of a pressurized cabin for much higher speeds at higher altitudes, but the extra weight and higher complexity lead to the decision to follow that option in a later stage. The use of oxygen masks is a likely option to increase cruise altitude and therefore the range and speed for ferry flights. As passengers often don't like to wear oxygen masks, our calculations are based on low altitudes.

The growth of the civil helicopter market is as a sign for the increasing need for runway independent transportation of individuals.

The use of helicopters is limited due to:

- The very high price per service (limiting the number of people that can afford the high price for the provided time saving)
- The limited range of helicopters (increasing the price due to refuel detours and reducing the time saving benefit)
- The political pressure to limit helicopter operations because of the noise impact.

We see economic potential, when we have a distinctively better cruise performance at a lower price per service than modern and near future helicopters used for business transport.

As a rough sizing we work with the following data:
Wing span: ~10m
Empty weight: ~2000kg
Engine power: ~1100kW
Range: >= 1000km after VTO with 3 PAX
Economical cruise speed: >=280km/h at 3000m MSL

Fast cruise speed around 360km/h with much lower fuel consumption than helicopters cruising at around 225km/h.

We expect the concept to be scalable for smaller and bigger sizes, as well as for much faster speeds. When scaling to more than 9 passengers, an adjusted design might be necessary. We don't expect a market for a VTOL airliner for 20 or more passengers in the near future. The advantages of VTOL aircraft are in the independency of infrastructure and the ability to transport people according to their very individual need. The bigger the aircraft the more infrastructure you need and the less you can adjust for individual travel requirements.

The goal of the Ray design is to provide the users with a highly independent aircraft. It can be used as a door to door transportation means – if allowed by the regional restrictions. The Ray needs no runway for takeoff or landing. On the ground it can be moved around with the help of the landing gear (it doesn't need any extra equipment to be moved contrary to many helicopters with skids). The engines consume jet-A1 fuel available at all airports and most heliports and airfields. When operating from runways in cruise mode, the aircraft is operated like a conventional aircraft in the propeller or light turboprop class.

WHY AN UNORTHODOX LAYOUT OF THE WING AND THE WING-FANS?

The quadrocopter layout leads to good control in hover and the slow part of the transition.

Fan-in-wing designs are efficient for slow horizontal speeds. For a balanced design the fans should be arranged around the center of gravity (CG). With increasing forward speeds the efficiency of the fans drops.[3] [9] Especially the fans located in the middle or at the leading edge of the wing lose almost all effect to contribute to lift.[3] With an arrangement of two fans in a row (per wing) we can use all fans for vertical takeoff, but shift the power to the rear fan to remain in the most efficient configuration[3] with growing forward speed. In addition we create a pitch-down moment with the rear fans[3]. Therefore we can compensate the loss in efficiency of the fans and the expected pitch-up-moment of the transition.

A lower disc load leads to higher efficiency of the wing-fans and thus to lower overall power need.[4] The power need is a determinant factor for the system price and for the operational costs.[4] It is therefore of main interest to keep the disc load in a moderate range for a civil fan-in-wing VTOL aircraft.

Fan-in-wing designs with moderate disc loads have very high Reynolds numbers and a low wing loading. A low wing loading leads to small induced drag when compared to conventional aircraft. => Adding wing surface at the trailing edge (area with very high Reynolds numbers) generates less drag than adding the same area by extending the wingspan. For the special situation of the Ray design it leads to less drag in cruise flight, when we decrease the wing aspect ratio.

In classical aircraft design the wing area gets defined by the maximum takeoff weight (MTOW) and the desired takeoff speed. The wing aspect ratio is then limited only/mainly by structural reasons. A high aspect ratio is a good optimum for most type of aircraft (from the glider up to the fast and high flying airliner) to reduce overall drag in cruise flight, but it's not the best choice for the fan-in-wing design Ray.

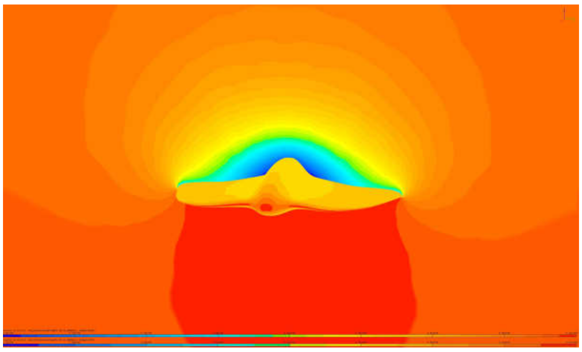


Figure 2. CFD analysis: Pressure distribution in cruise flight

The openings of the wing-fans get closed during or at the end of the transition to get aerodynamic optimal airfoils in cruise flight.

To illustrate the unexpected inversion of the classic aircraft design principle we show a simple comparison of three alternative design options:

1. Ray design (figure 3): Wing area: 63.7m^2
2. Ray with added wing to increase aspect ratio (figure 4): Wing area: 68.7m^2
3. Ray with only two fans (figure 5): Wing area: 67.3m^2

The drag was calculated for the wing, creating a lift of 24’525N at an altitude of 3000m and a speed of 100m/s. The calculations were done with the help of XFLR5. We verified the results with FLZ_VORTEX and simple analytic formulas. All calculations lead to similar results and the same conclusion: the wing with lower aspect ratio (AR) and a smaller wing area (figure 3) generates the least drag.

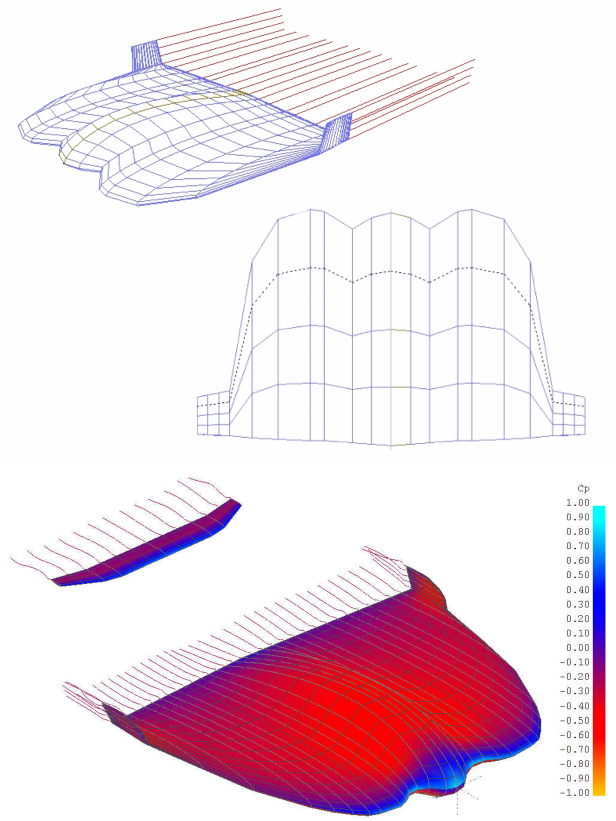


Figure 3. Ray design: aspect ratio: 2.2 -> drag: 2’290 N

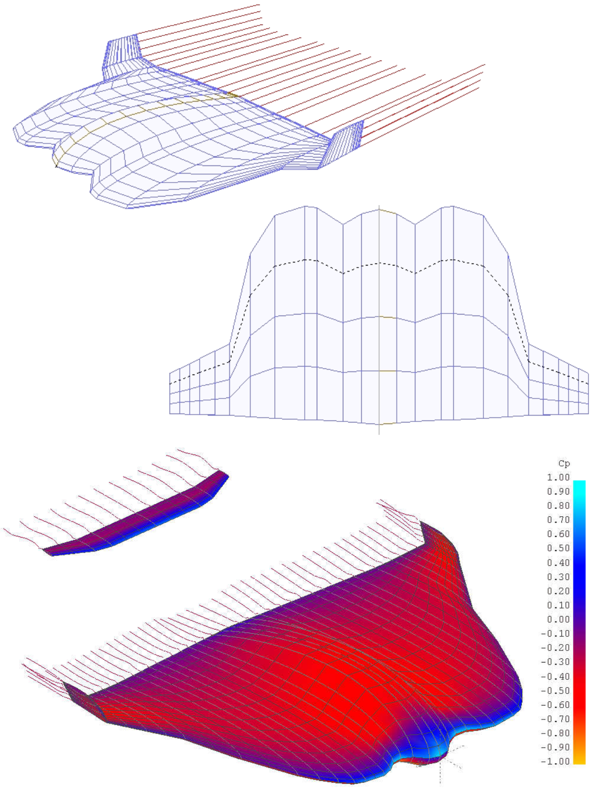


Figure 4. Ray with added outer wing to increase aspect ratio: aspect ratio: 2.75 -> Drag: 2’344 N

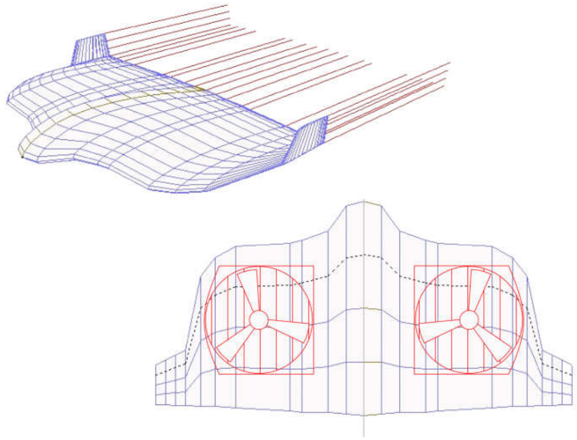


Figure 5. Ray with only two fans: aspect ratio: 2.8 -> Drag: 2’305 N

We conclude that neither variant 2 (figure 4) nor 3 (figure 5) lead to better cruise efficiency. Both variants would have further disadvantages.

Variant 2 would lead to extra weight. The extra weight is the weight of the extra wing portion plus the additional weight for reinforcement of the inner wing structure for slightly higher gust loads of the wing tips.

Variant 3 (figure 5) with only 2 wing-fans (the fan openings get closed for cruise flight with this variant as well, they are just shown to depict the position and the relative size) has a fan diameter which is 20% bigger than the big fan of the suggested Ray design. This increase in fan diameter is needed, if the total fan area and the vertical takeoff power should stay the same. This increase of the fan diameter leads to a bigger wing span. In addition the fan construction needs to become thicker to encase the stronger fan drives and to cope with the stronger forces. The aircraft of figure 5 would be more difficult to control in hover and transition. With only one fan per wing, we can't control pitch and we can't adjust for a displaced center of gravity as easy as with 2 fans per wing. With 2 fans per wing we can respond to the pitch-up effects and profit of the better efficiency of the rear fans in transition with increasing forward speed. This would be almost impossible with only one fan.

For the simple formulas we adjusted the induced drag with an Oswald factor of 0.9 since more detailed 3D computational fluid dynamics (CFD) analysis showed an almost elliptic lift distribution (see figure 2). Dr. Jan Roskam estimated that an Oswald factor in the range between 0.85 and 0.9 would fit our design.

With simple analytic formulas we get for the Ray design:

Zero lift drag:

$$C_{W,Fl_0} = C_{rkomp} \cdot \left[1 + C_1 \cdot \frac{d}{l} + 100 \cdot \left(\frac{d}{l}\right)^4\right] \cdot C_2 \cdot \frac{S_{wet\,FL}}{S_{ref}}$$

$$= 0.00611$$

Induced drag:

$$C_{W,Fl_i} = \frac{{C_{A,Fl}}^2}{\pi \Lambda e} = 0.00226$$

Resulting to a total drag force of: *2423N*

Especially the constraint to encase a certain size of fans leads to the necessity to increase the wing area when increasing the aspect ratio. At the given low wing loading and high Reynolds numbers (>40 million) the benefit from the smaller induced drag is less than the penalty for the bigger wing area.

A conventional aircraft of this size would have a lower wing area and a much smaller wing depth than the Ray design. When we increase the aspect ratio of a conventional design, we can keep the wing area unchanged. The total drag of a conventional design gets lower when we increase the aspect ratio, since the induced drag gets reduced and the factor for the wing area stays unchanged.

The optimal arrangement for the Ray design is influenced by the specific disc-loading. The fan size leads to the wing size and the wing depth. The other main influences for the optimum are the desired cruise speed and the cruise altitude.

When optimized completely for a fast cruise speed (very small aspect ratio as shown in figure 3), the induced drag gets very big at slower speeds at the end of the transition. If we would decide to improve the slow flight characteristics, the design might change more to a shape as shown in figure 4. The design as shown in figure 4 leads to a slightly higher drag in fast cruise, but has much better performance and handling qualities in slow flight.

The low lift coefficient (and thus relatively low induced drag) in fast cruise flight is also a result of the lack of a pressurized cabin. It would be more efficient to fly this wing (or a more conventional wing of this size with this little weight to carry) in higher altitudes, at higher angles of attack. (But a pressurized cabin would increase the weight for vertical takeoff and thus the costs of the system.)

We want to point out, that the Ray wing layout is an optimum only for the given constraints. It is often suggested to increase the wing span to improve aspect ratio. This doesn't make sense for the cruise flight for the Ray design. With adjusted conditions the optimum for the aspect ratio might increase (for slower speeds and/or higher loads and/or higher altitudes) or even decrease (for faster speeds).

The Ray layout can be further improved in detail, especially with winglets, optimized wing to fuselage blending and a specific choice of airfoils.

The winglets of the Ray design are used to reduce the induced drag (similar to increased wing span, as shown in figure 4), but also to improve stability.

The airfoil design has to deal with the constraint that the fans and the fan drives have to fit into the wing. But beside that we can optimize for specific Reynolds numbers and the 3D airflow situation.

Optimal wing span for simplified example

With analytic formulas we want to derive the optimal wing span for a minimal cruise drag of a very simple fan-in-wing design. The calculation is only valid with the precondition to have a fixed wing area to encase the four wing-fans and the specific dimensions. This leads to a fixed average wing depth for the additional wing. What we want to show is that there is a non infinite optimum for the wing span for a minimum drag, if the average wing depth is kept constant.

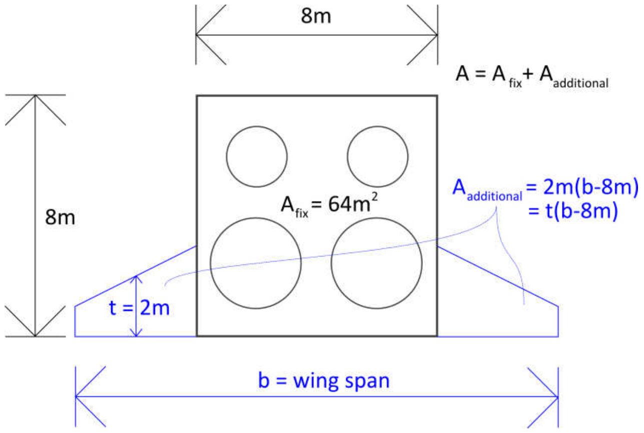


Figure 6: Simple layout with fixed wing depth

$$\text{Drag: } D = \frac{\rho v^2}{2} A(C_{W0} + C_{Wi}) \qquad (1)$$

$$D = \frac{\rho v^2}{2}\left(A_{fix} C_{W0fix} + A_{add} C_{W0add} + A C_{Wi}\right) \qquad (2)$$

$$C_{Wi} = \frac{{C_A}^2}{\pi \Lambda e} \qquad (3)$$

$$C_A = \frac{2L}{\rho v^2 A} \qquad (4)$$

$$K1 = \frac{\rho v^2}{2}; \qquad K2 = A_{fix} C_{W0fix} \qquad (5)$$

$$D = K1\left(K2 + t(b-x) C_{W0add} + A\,\frac{{C_A}^2}{\Pi \Lambda e}\right) \qquad (6)$$

$$D = K1\left(K2 + t(b-x) C_{W0add} + A\,\frac{4L^2}{\Pi \Lambda e \rho^2 v^4 A^2}\right) \qquad (7)$$

$$K3 = \frac{4L^2}{\pi e \rho^2 v^4}; \quad K4 = C_{W0add}\, t; \; K5 = -x * K4 \qquad (8)$$

$$D = K1\left(K2 + K4 \cdot b + K5 + K3\,\frac{1}{\Lambda A}\right) \qquad (9)$$

$$\text{Aspect ratio: } \Lambda = \frac{b^2}{A} \qquad (10)$$

$$D = K1\left(K2 + K4 \cdot b + K5 + K3\,\frac{1}{b^2}\right) \qquad (11)$$

$$Min(D) \to D' = 0 \to D' = K1\left(K4 - K3\,\frac{2}{b^3}\right) = 0 \qquad (12)$$

$$\frac{1}{b^3} = \frac{K4}{2K3} \qquad (13)$$

$$b_{min\,drag} = \sqrt[3]{\frac{2K3}{K4}} = \sqrt[3]{\frac{8L^2}{\pi e \rho^2 v^4 \cdot C_{W0add}}} \qquad (14)$$

With
$C_{W0add} = 0.016$ 0-Lift drag of NACA 63-612 for Re 10M
density of air at 3000m: $\rho = 0.909\text{kg/m}^3$
air speed: v = 100m/s
average wing depth of addition: t = 2m
wing span of square: x = 8m
lift force: L = 24’525N
Oswald factor: e = 0.9

we get for the optimal wing span:
$b_{\,min\,drag} = 8.62\text{m}$ (15)

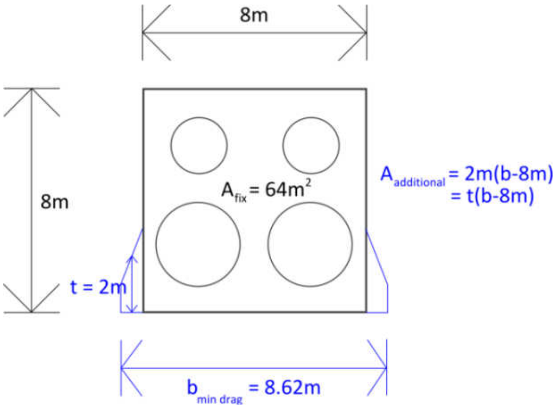


Figure 7: Simple layout; minimum drag wing span

The optimal aspect ratio for this mathematical example is only 1.14.

The drag with a wing span of 8.62m results to: 2497N

We know the real drag would be bigger due to the non-optimal attachment of the additional wings. We use geometric primitives so the calculation can be easily followed. The numeric result is only an example and not to be used for real aircraft.

Wide known formula 3 is validated for Λ values from 1 to 7 by experiments with rectangular wings in the book of Schlichting&Truckenbrodt[5] (formula 7.31 and figure 7.9. in the book) with an Oswald factor of 1.0.

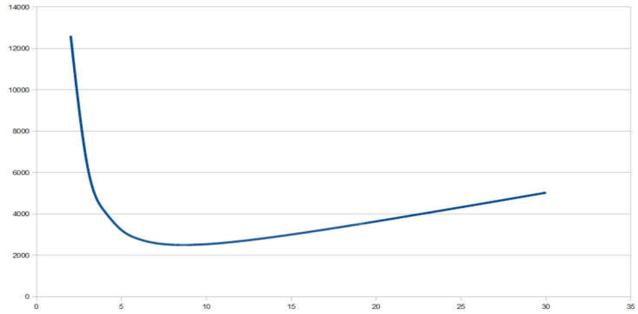


Figure 8: Drag in function of the wing span for the sample

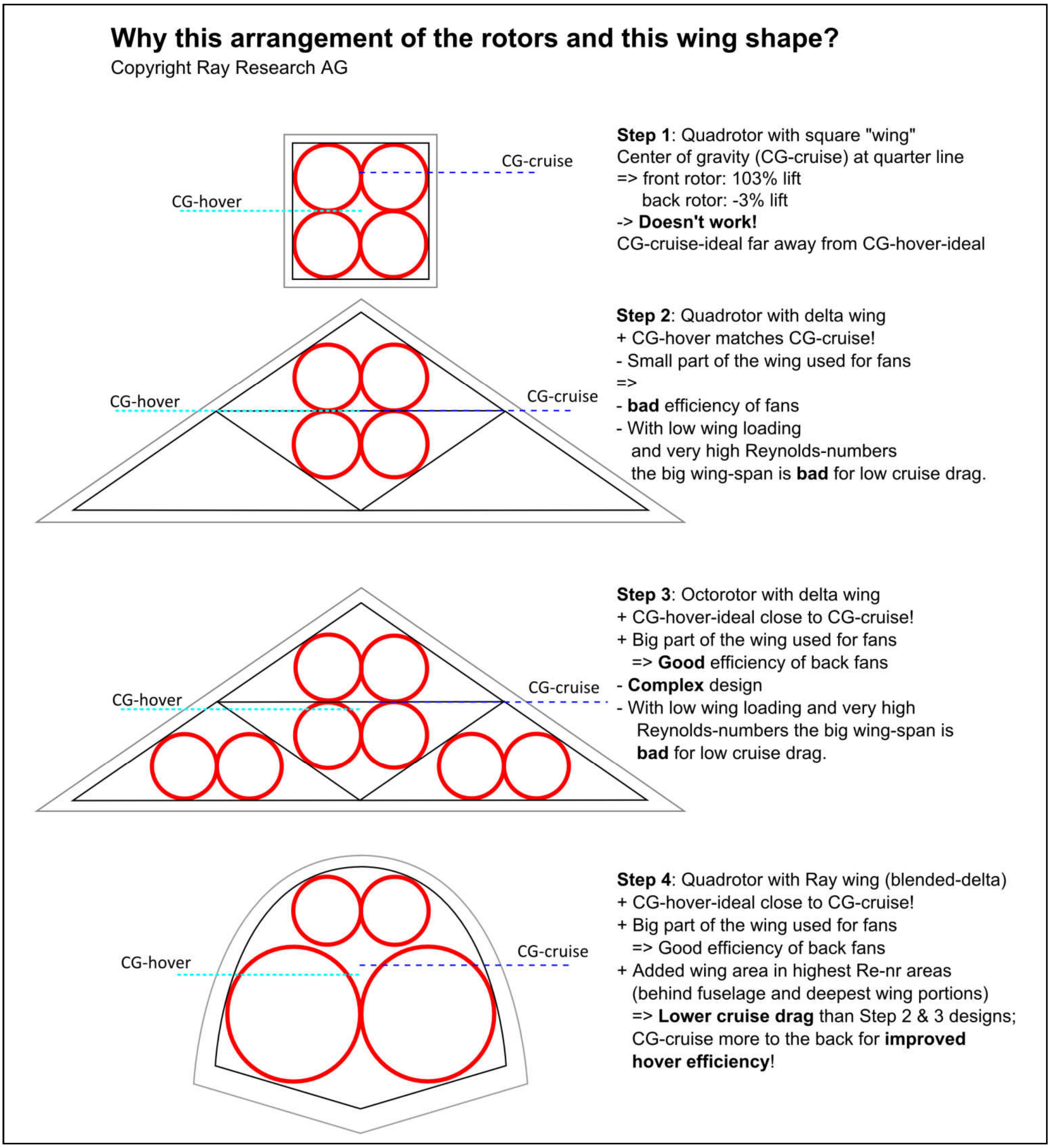
As shown in figure 8, an increase of the wing span above the optimum has little influence. A decrease of the wing span would lead to a drastic increase of drag.

The resulting small optimal wing span and aspect ratio are defined by the unconventional restriction to have a fixed average wing depth.

Without this constraint, the term with K4 (resp. C_{w0add} and A_{add}) would be eliminated and the optimum wing span would result to infinity with a wing depth of zero. This mathematical “optimum” for conventional designs is limited in the real world by structural and maneuverability issues. Further C_{w0} isn’t constant for varying Reynolds numbers.

Center of gravity for hover and cruise mode

In addition to the efficiency in cruise and hover, we have to make sure the lift forces match the center of gravity (CG) of the aircraft in all flight modes. The allowed CG range for hover must match the allowed CG range for cruise for all normal angles of attack (AOA). Only the intersection of the allowed CG ranges of hover, transition and cruise is the allowed CG range for the system.



Why this arrangement of the rotors and this wing shape?

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Step 1: Quadrotor with square "wing"
Center of gravity (CG-cruise) at quarter line
=> front rotor: 103% lift
back rotor: -3% lift
-> **Doesn't work!**
CG-cruise-ideal far away from CG-hover-ideal

Step 2: Quadrotor with delta wing
+ CG-hover matches CG-cruise!
- Small part of the wing used for fans
=>
- **bad** efficiency of fans
- With low wing loading
and very high Reynolds-numbers
the big wing-span is **bad** for low cruise drag.

Step 3: Octorotor with delta wing
+ CG-hover-ideal close to CG-cruise!
+ Big part of the wing used for fans
=> **Good** efficiency of back fans
- **Complex** design
- With low wing loading and very high
Reynolds-numbers the big wing-span is
bad for low cruise drag.

Step 4: Quadrotor with Ray wing (blended-delta)
+ CG-hover-ideal close to CG-cruise!
+ Big part of the wing used for fans
=> Good efficiency of back fans
+ Added wing area in highest Re-nr areas
(behind fuselage and deepest wing portions)
=> **Lower cruise drag** than Step 2 & 3 designs;
CG-cruise more to the back for **improved**
hover efficiency!

Figure 9. Schematic explanation of the Ray wing design

EFFECTS OF USING TILT-DUCTS IN COMBINATION WITH FAN-IN-WING

The Ray design uses tilt-ducts attached to the stabilator far behind the center of gravity (CG) for a thrust-vectoring control around the lateral axis. This enables perfect control of the angle of attack (AOA) in slow flight and especially in transition.

When tilted 90° down, the tilt-ducts lead to additional lift force and additional pitch control in hover flight.

Historical fan-in-wing designs suffered from undesired pitch up moments in transition and difficulties controlling the transitions.[6 7 8]

When moving forward, the fan-in-wing arrangement leads to asymmetric effects from the interaction of the fan induced air flows with the surrounding wings and the horizontal stabilizer:

1. Increased air speed at the upper leading edge of the wing due to the ingestion of the fans leads to additional lift in front.[3 6 9]
2. Increased pressure on the lower side of the wing upstream of the fan due to the blockage effect of the fan jet.[3]
3. Additional down force at the wing trailing edge due to fan induced airstreams (upper and lower side of the wing)[3 6 9]
4. The rear fans induce an additional circulation[3 9]. The additional circulation interacts with the horizontal stabilizer.

The result of all effects found in the quoted work for fan-in-wing arrangements lead to an additional pitch-up moment as soon as the aircraft moves forward. It is therefore of crucial importance to generate a controllable pitch-down moment[6]. The Ray design uses the thrust-vectoring capabilities of the tilt-ducts to provide a controlled pitch-down moment.

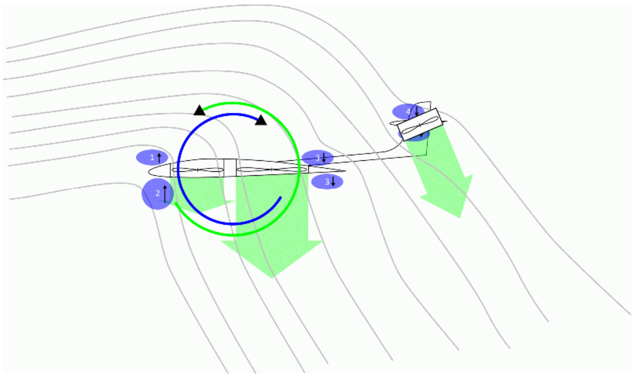

Figure 10. Pitch-up effects and pitch control

At the beginning of the transition (with small forward speed and high fan speeds), the fan induced downstream is stronger and has a higher angle of attack (AOA) at the stabilizer than at the end. Nevertheless we expect the effect 4 to generate a maximum moment close to the end of the transition. This effect is a result of the airstream interacting with the stabilizer (with a high AOA) in the stall region at the beginning and middle part of the transition. Only when the AOA of the fan induced airstream decreases to below 10° the pitch-up moment generated by the horizontal stabilizer becomes significant.

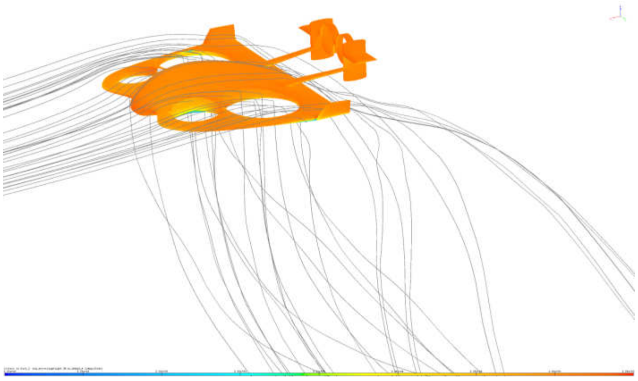

Figure 11. CFD analysis of the transition showing the influence of the fans to the streamlines

Tilt-ducts are a good means for thrust-vectoring and are efficient as propulsion in cruise flight, if optimized in size and design for the cruise speeds.[10] As the lift force is generated by the wing-fans, the tilt-ducts can be optimized for fast cruise flight.

The duties of the tilt-ducts in hover and early transition are the control of acceleration along the longitudinal axis and the pitch control. In hover flight the tilt-ducts are directed downward to control the pitch angle by thrust variation and to maneuver the aircraft forward and backward by tilt angle variation. In addition they help generating some lift.

To accelerate from hover to cruise flight, the tilt-duct angle is changed gradually from 90° down up to horizontal.

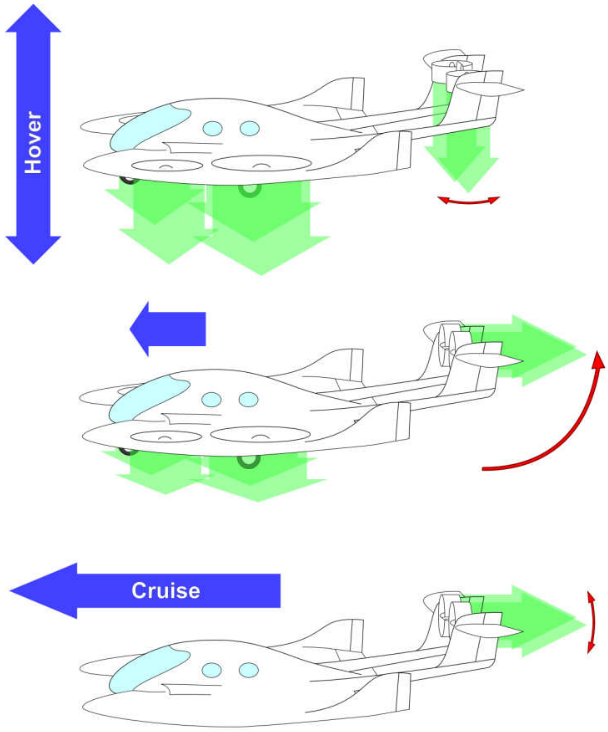

Figure 12. Schematic drawings of the flight modes

When the tilt-ducts are tilted to horizontal for propulsion at faster speeds the thrust is used for forward acceleration and the tilt angle for pitch control.

When the tilt-ducts are tilted between 90° down and horizontal, a pitch down moment and forward force is generated by the thrust. By turning the ducts we change from hover flight control, to transition control and further to optimal cruise propulsion. (See figures 10 & 12) In transition the pitch down moment and forward acceleration are controlled with the help of the adjusted thrust and tilt angle. This way, this arrangement perfectly fits the need to compensate the described pitch up effects (pitch down moment needed) in transition. The thrust reserve of the tilt-ducts in the transition must be designed big enough to easily compensate the expected pitch up moment.

In the transition from cruise flight to hover, we need to slow down the aircraft. Thus we provide less thrust to the ducts. For generating the same pitch down moment in transition, we have to apply a bigger tilt angle to the tilt-ducts (in comparison to the acceleration transition with higher thrust). The bigger tilt-duct angle results in bigger drag, which helps to slow down the aircraft.

CONCLUSIONS

The four big wing-fans of the Ray enable an efficient and good to control hover flight for vertical takeoff and landing. In addition we explain how the unorthodox Ray layout is an optimum for this fan-in-wing design. The layout leads to a relatively efficient and economic cruise flight with closed wings. The tilt-ducts in the back provide an efficient means for cruise flight propulsion. Because of their position, their orientation and the thrust vectoring capabilities, the tilt-ducts perfectly fit the needs for a safe transition.

Therefore we conclude that the described aspects of the Ray design fit well the needs of the civil market.

Current and future work

Current and future scientific work focuses on CFD and wind tunnel simulation of the crucial transition phase. Currently we focus on the discussed interaction of the wing-fans with the wings and the stabilator (chapter “Effects of using tilt-ducts in combination with fan-in-wing”) to obtain more dependable numerical results. For the cruise mode the stability and optimal wing layout for the whole flight envelope needs to be further studied and improved.

The choice of engines and power distribution, which wasn’t addressed in this paper, needs to be discussed and compared to alternative approaches. The main parameters of the power system are weight (also the distribution of the weights of the power system parts for the influence on the CG), efficiency, reliability, safety, availability (certified by FAA) and costs.

Parallel to the theoretical work, we continue to bring scaled aircraft into the air. With increasing size, performance, detail and complexity we approach our goal of the manned flying VTOL Ray.

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