# FEASIBILITY STUDY OF THE INSTALLATION OF AN ADDITIONAL "OVER LIFT" WING ON THE CH47 CHINOOK FOR CRUISE PERFORMANCE IMPROVEMENT THROUGH THE LIFT-COMPOUND APPROACH

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## ABSTRACT

The tandem rotor configuration is particularly convenient for the lift-compound approach in helicopters. In fact, the additional wing is positioned between the two rotors in an area that is marginally interested by the airflow in vertical flight. On the contrary, in horizontal flight, the airflow accelerated by the frontal rotor directly invest the wing improving its lift. A very thin wing with a short chord and a relatively large span can be manufactured with the same technology of the rotor blades. If this wing is fixed without control surfaces, the additional weight can be extremely limited. A concave-convex high lift airfoil can be used. This airfoil is relatively stiff due to the large bending moment of inertia. A skin stressed structure can be used for the additional wing to obtain also a large torsional stiffness. This lightweight wing can be installed on the helicopter when required and it can be optimized to a defined flight condition. In our case the optimization was performed for cruise. With a very limited weight increment and with a lift penalty within the simulation approximations, the cruise fuel consumption can be halved. The result is impressive for ferrying and long range passenger transport operations, where load capacity can be fully exploited only by increasing the fuel load. In this case a helicopter like the Chinook can perform long range missions with a significant increase in operational capability.

**Keywords:** tandem rotor, helicopter, lift-compound, cruise, range.

## INTRODUCTION

The tandem rotor configuration is particularly convenient for the lift-compound approach in helicopter. In fact, the additional wing is positioned between the two rotors in an area that is marginally interested by the vertical flow in vertical flight. On the contrary, in horizontal flight, the airflow accelerated by the frontal rotor directly invest the wing improving its lift. A very thin wing with a short chord and a relatively large span can be manufactured with the same technology of the rotor blades. If this wing is fixed without control surfaces the additional weight can be extremely limited.

This study starts from the Boeing Vertol Model 347. In this helicopter the modifications from the original Chinook CH-47C were: the addition of a fourth rotor blade in each hub, with an increase of 762mm in length. Fuselage lengthened by 2794mm and aft mast height increased by 762mm. Other modifications were: a retractable main gear, fly-by-wire system and a gondola which could be lowered from the cockpit where a pilot (facing to the rear) could fly the Chinook. However, the main variation was a detachable wing which was controlled hydraulically to vary incidence and to rotating up to 90° while in hovering. This modified Chinook proved too ambitious for its time.

The conclusion from the final report of RDTE AVSCOM PROJECT NO. 72-12, USAASTA PROJECT NO. 72-12 of OCTOBER 1972 are: "The US Army Aviation Systems Test Activity conducted the Phase II technical evaluation of the Boeing-Vertol Model 347 winged helicopter during the period 3 through 11 April 1972. The Model 347 winged helicopter, a derivative of the CH-47 transport helicopter incorporating a variable incidence wing with normal acceleration load-sensitive flaps, was tested at the contractor's facility near Philadelphia, Pennsylvania. The evaluation was conducted to determine the improvements provided by addition of a wing system to a transport helicopter. Compliance with the provisions of military specification MIL-H-850IA was determined. Evaluations of the variable incidence wing system and the retractable landing gear system were also made. With the wing in the hover position, out-of-ground-effect hover performance of the Model 347 winged helicopter was similar to the unwinged aircraft. Both the winged and nonwinged Model 347 helicopter could hover out of ground effect using less power than could the CH-47C. Level flight performance at a heavy referred gross weight (54, 000 pounds) was improved over both the nonwinged helicopter and the production CH-47C. Addition of the wing to the Model 347 helicopter did not significantly change the generally excellent handling qualities reported for the nonwinged version of the aircraft. The strong longitudinal stability exhibited by the aircraft reduced pilot workload in maintaining trim airspeed and pitch attitude. Only minimal trim changes in all control axes were required when transitioning between climbs or descents and level flight. The Model 347 winged helicopter failed to meet the requirements of five paragraphs of MIL-H-8501A. Twelve shortcomings were identified. The most significant of these shortcomings were the high pilot workload required to accomplish takeoffs and landings with the wing incidence control system functioning in the automatic mode, an excessive longitudinal oscillation in turns above 30-degrees angle of bank at 85 knots calibrated airspeed, the excessive sensitivity of rotor speed to thrust control rod position during auto rotational flight, slippage of the thrust control rod at high power settings, and an excessive 8-per-revolution vibration during hover, approach to a hover, and in left sideward flight at 30 knots calibrated airspeed. The variable incidence wing and normal acceleration load-sensitive flaps installed on the Model 347 winged helicopter increased the accelerated flight capability of the aircraft. Stabilized turns in excess of a 60-degree angle of bank (2.0 load factor) were accomplished at all test airspeeds without overstressing the rotor or associated control system components. The retractable landing gear system reduced parasite drag and resulted in an airspeed increase of approximately 4 to 5 knots at indicated airspeeds above 120 knots. The advantages gained with the wing and the retractable landing gear are gained at the expense of increased weight and complexity". On the contrary the project described in this paper starts from a different approach. In fact, this paper evaluates the idea to add a fixed lightweight wing to the existing Chinook to improve range (or payload). The new wing is a very simple, fixed component without any control surface. It may be installed when necessary and when convenient for the mission. In fact, the wing is extremely convenient for long range missions. For lift work at short range the extremely light penalty in weight and lift-capacity makes this solution slightly less appealing. As it will be seen in the following parts of this paper, the position, the chord length and the elongation of the wing proved to be critical.

## Initial considerations

The software used in this work is Solid Works Flow Simulation on a very basic Windows based Personal Computer [2-4]. The design started from the assumption that fixed wing lift is much more efficient than rotor one in cruise. In order to reduce the influence of the wing in take-off and hover, the wing should be as small as possible. For this reason, an Eppler 423II high-lift airfoil was selected, regardless to any consideration of the efficiency of the isolated wing. As in the original CH47, the CAD model has the rotor blades modelled with a VR-8 airfoil from last (tip) 15% of the blade, and the remaining part with the VR-8 airfoil. The twist is 12 degrees. The frontal and rear 3-blade rotors have inclination of 9 degrees and 4 degrees respectively (see Figures 1 and 2). The rotors rotational speed is 225 rpm.

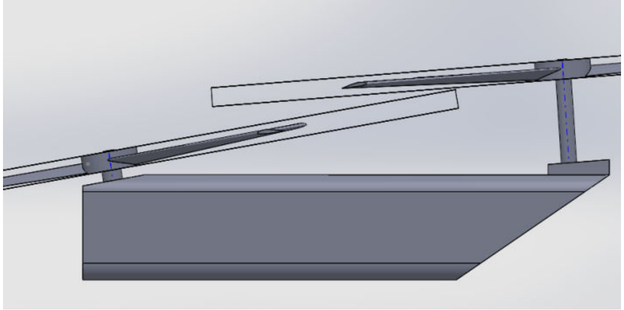

**Figure-1.** Lateral view of the CAD model.

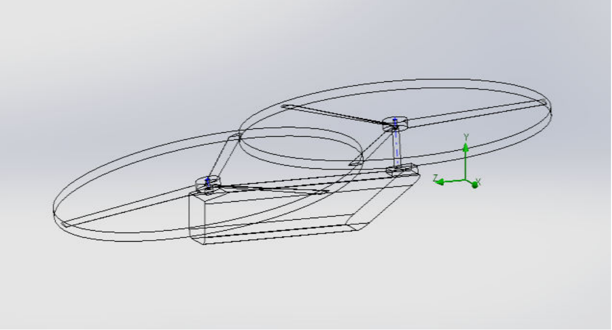

**Figure-2.** Wireframe axonometric view of the CAD model.

The most ambitious goal of this project is to investigate the cost-effectiveness of the use the horizontal flow component generated by the front rotor in order to generate an effect that could be termed "over-lift" on the fixed wing surface. This effect should be able to generate a lift far superior to the one of the "clean" wing. Therefore, the most interesting part of the CFD optimization focuses on the design of a wing geometry that can combine an increased cruise efficiency with the same maneuver envelope of the wingless helicopter.

## CFD model optimization

Even with the extremely efficient Flow Simulation software, the CAD model of the helicopter should be simplified for cost-effectiveness in terms of computer time. A comparative CFD simulation of the unwinged and winged CH47 is performed in this model. Therefore, the fuselage can be simplified at the extreme. In fact, iterative methods, such as conjugate gradient method and GMRES (Generalized minimal residual method), are used for the sparse matrixes for CFD simulation. With these methods the edges of the model are automatically and very efficiently "rounded-filleted" by the numerical matrix solver. In the CAD model used in this paper, the edged fuselage was filleted only where strictly necessary (Figures 1 and 2) [5-20].

## The interfering rotational region problem

In the Author's knowledge, the CFD simulation software does not allow to replicate the real operating condition with the 2 rotors running counterclockwise and sharing part of the volume of processed fluid. It was therefore inevitable to test two configurations that could get around to this limitation. The first configuration involves mounting the 2 rotors one over the other (Figures 1 and 2). The second configuration is based on the introduction of an additional fuselage section sufficient to remove the 2 rotors interference.

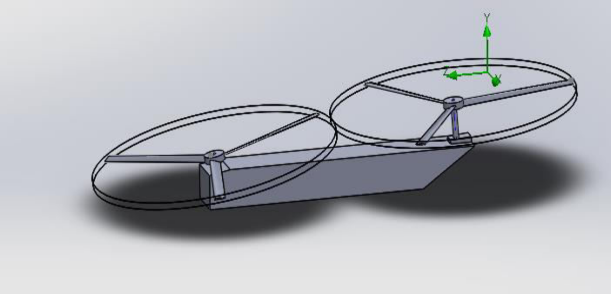

**Figure-3.** The "elongated fuselage" rotors configuration.

### First tests: hovering of the standard Chinook

The analysis began by testing the standard wingless configuration. In this case the blades pitch is 18 degrees as indicated on the helicopter technical manual [1]. The tests were performed both on the superimposed configuration (Figure-2) and on the “elongated fuselage” configuration (Figure-3). General data and results of these simulations are summarized in Table-1.

**Table-1.** General data and results of simulation: hover-original wingless Chinook.

| Description | Value | Unit |
|---|---|---|
| Rotor diameter | 60 | ft |
| Blade number per rotor | 3 | - |
| Blade pitch | 18 | Degrees |
| Rotor center distance superimposed (CH 47) | 11.94 | m |
| Rotor center distance elongated | 18.5 | m |
| Horizontal and vertical speed | 0 | - |
| Environmental conditions | ISA | - |
| Density altitude | 1000 | m |
| Local mesh of rotors | 5 | - |
| Global mesh | 5 | - |
| Curvature refiniment | 0.3175 | rad |
| Lift superimposed configuration | 285,000 | N |
| Lift elongated configuration | 300,000 | N |

As it can be seen the superimposed configuration gives acceptable values. Therefore, the work was focused on the superimposed CAD model.

### Lift compound concept

A lift compounded helicopter is a helicopter with a wing added to the fuselage. Usually the ¼-chord of the wing is aligned with the Gravity Center (CG) to minimize the pitching moments on the airframe. In tandem rotor helicopters the pitching moments are countered by some additional tilt of the rear rotor TPP (Tip Path Plane), which affects the trim state of the rotor and introduces a small reduction in efficiency. In general, the wing aerodynamic is affected by the free-stream flow and by the rotor downwash, both of which greatly affect wing additional lift and drag. A very simplified initial model can be used for a first design of the lift compounded helicopter. The most critical parameter is the wing incidence *i*, on the helicopter center line that greatly affect performance and efficiency. The wing can be fully or partially in the rotor wake, depending on the values of limiting leading edge and trailing edge skew angles $\chi_1$ and $\chi_2$, compared to $\chi$, as shown in Figure-4., i.e.,

$$X_1 = \arctan\left(\frac{R - \frac{1}{4} C_{wing}}{d_{RW}}\right) \quad (1)$$

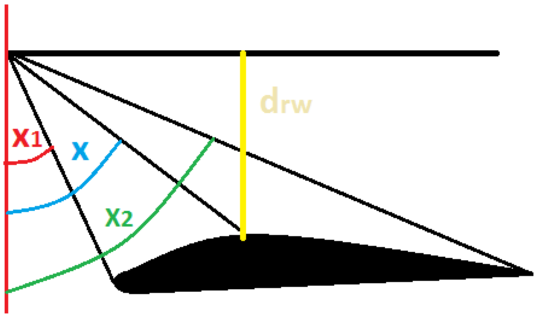

**Figure-4.** Simplified wing model [2].

$$X_2 = \arctan\left(\frac{R + \frac{3}{4} C_{wing}}{d_{RW}}\right) \quad (2)$$

In the tandem rotor the wing is fully outside of the wake. In this case, it is possible, as a first approximation, to assume that the freestream velocity is fully horizontal and the slipstream velocity is fully vertical, which gives for the total velocity $v_{total}$(3) and for the airflow angle of attack α (4):

$$v_{total} = \sqrt{v_\infty^2 + w^2} \quad (3)$$

$$\alpha = \arctan\left( w / v_\infty \right) \quad (4)$$

Therefore, the effective wing angle of attack αeff can be calculated with equation (5).

$$\alpha_{eff} = \alpha + i - \alpha_{TPP} \quad (5)$$

It is then relatively easy to calculate the Lift and Drag of the airfoil by using 2D-CFD software. On the contrary the helicopter body interference with the wing is very difficult to evaluate and requires a full 3D CFD simulation.

Wing design started from the choice of the Eppler 423 high lift airfoil. This choice is due to the consideration that the lift efficiency of a fixed wing is always better than the one of a rotating one. Therefore, it is convenient to maximize the lift given by the wing even at the expense of a not very efficient fixed wing. The negative influence of the fixed wing in takeoff and hover is minimized with a small chord wing. Therefore, a high lift airfoil seems to be convenient. Moreover, the vicious, low speed stall problem is negligible for VTOL vehicles. The wing design is optimized for cruise condition. The CH 47 has a cruise speed of about 256 km/h (160 knots) at about 1000m (3000ft). A very simple wing design was adopted with high elongation to achieve a good aerodynamic efficiency. The rectangular wing is untwisted and has null dihedral and sweep angle. It will be possible to work on these parameters to further optimize wing performance. In any case, the basic idea of this work is to manufacture the wing with the same technique of the rotor blades. No control system is to be applied on the wing except for a system to fold or to disassemble the wing for storage or convenience. In this way it is possible to obtain very lightweight wings that will not affect the helicopter empty weight in a significant way [21-27].

During this first phase of study it was very important to carefully evaluate the Lift and Drag coefficients with the aim to optimize the angle of attack of the wing and also its correct positioning. It was demonstrated that it is convenient to position the wing is just on the fuselage. This configuration has to be checked with interference with rotor blade tips in the various flying conditions. However, in this preliminary study this interference has been considered negligible. The range of tested models had elongations from 9 up to 16. The best configuration proved to be about 14. The wing span range is from 10 to 16m with cords from 0.85 up to 1.5 m. Single and multiple wings configurations have been also tested with poor results (Figure-5). Also different, more efficient airfoils were included in early tests without good results.

## Winged configuration optimization

At the end of this first exploratory phase of the winged simulation, the best configuration had a wingspan of 13 m and a chord of 1m (elongation 13). The best longitudinal wing position is with wing aerodynamic center on the vehicle gravity center.

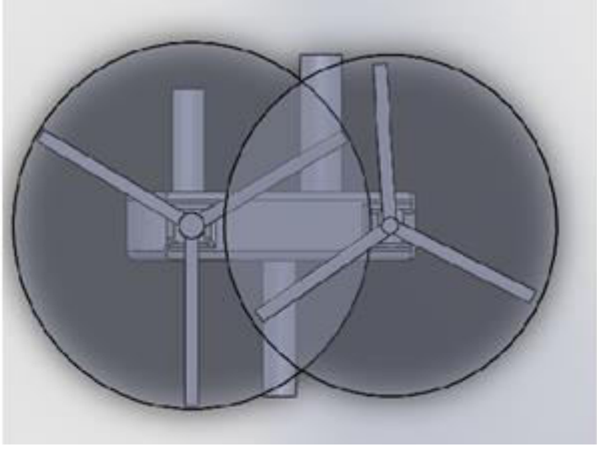

**Figure-5.** Three wings configuration.

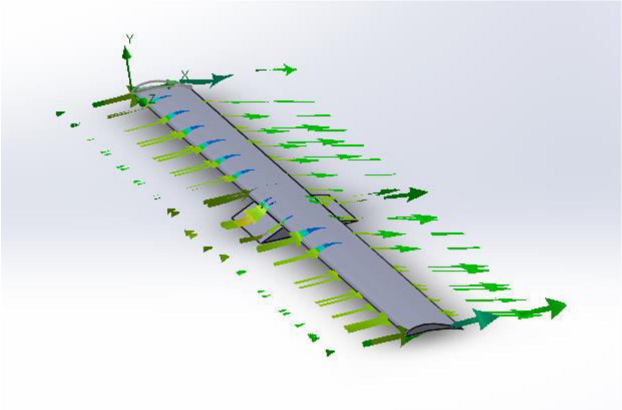

**Figure-6.** "wing alone" simulation with 7.5 degree incidence.

Initially, the angle of incidence was fixed at 7.5 degress, that for the wing alone is a high efficiency (Cl/Cd) value. At the cruise speed (160 knots) the lift of the wing alone is about 45,000N (Figure-5). The contribute of this wing to the total lift on the complete Chinook with wing is 63,000N, while the rotors give about 430,000N. In this case the rotor blades have a pitch angle of 4 degrees. The 40% increase of the wing lift from 45,000N to 63,000N is due to the frontal rotor downwash. As we will see in the following part of this paper the downwash has a large influence of wing performance. This result is very important since it is clear that there is a strong “over-lift” effect produced by the horizontal flow component developed by the front rotor. This flow has velocity, pressure and density characteristics that allow a remarkable increase in wing lift, obtained simply by exploiting energy that has already been produced and which is therefore not dispersed but recycled for the purpose of lift. This fact can be seen as an almost “free” energy benefit of the installation of the wing in the helicopter, therefore increasing the payload. This would result in a significant reduction of fuel consumption with possible increase in range and payload. In Figures 7, 8 and 9 it is possible to see that the flow on the wing is not symmetric.

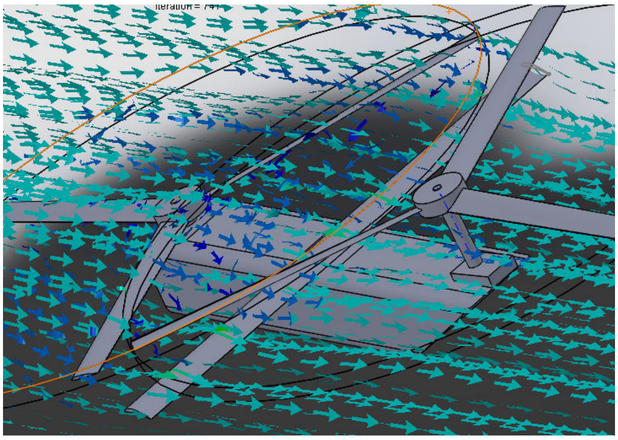

**Figure-7.** Flow on the wing in cruise.

The right wing has slightly more lift than the right wing. In the final configuration it may be convenient to increase slightly the left wing length to avoid the necessity of compensation from the helicopter controls.

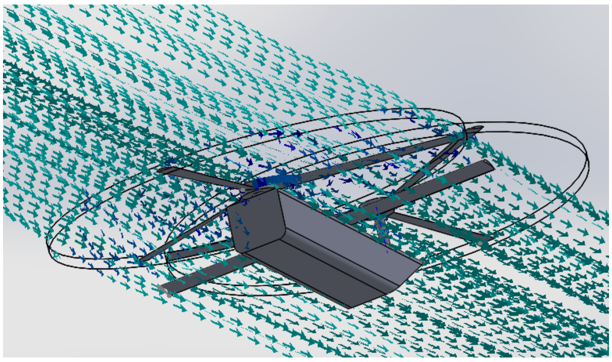

**Figure-8.** Winged helicopter in cruise.

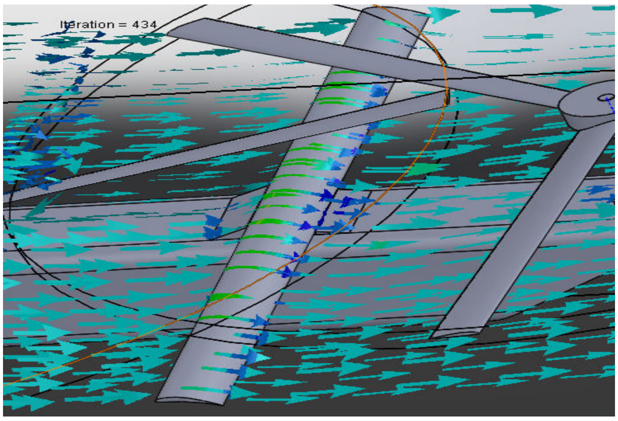

**Figure-9.** Zoom in on the wing of the helicopter.

The velocity vectors that invest the helicopter frontally are accelerated by the rotor then directed to the wing with a correct angle of less than 15 degrees. Initially, a slowdown occurs as air encounters the front rotor. Then the air is accelerated and pushed toward the wing. This fact gives the “over-lift" to the wing.

## Winged configuration efficiency optimization

In general, the addition of a wing on a helicopter can be helpful for improving performance at lower airspeeds or in relatively low speed helicopters like the CH47. This is due to the fact that the propulsive force of a helicopter is still generated by the rotor, which has to tilt progressively forward to reach higher airspeeds. At higher airspeed wing soon penalizes the overall performance of the aircraft because it eventually creates a significant negative lift force and corresponding drag. Therefore, the benefit of the fixed wing it restricted to a well defined speed.

The optimum angle of attack for this speed (the cruise speed) was searched with the Golden Section Method. The goal was to maximize the lift in cruise. An optimum angle of incidence of 14.5 degrees was found. This value was reduced to 12.5 degrees to optimize efficiency. In addition, the wingspan was increased up to 15.7m. The general data and results of these simulations with this new configuration are summarized in Table-2.

**Table-2.** Data and results of CH47 with 12.5-degree incidence wings.

| Description | Value | Unit |
|---|---|---|
| Wing span | 15.7 | m |
| Wing chord | 1 | m |
| Elongation | 14 | - |
| Incidence | 12.5 | degree |
| Distance of Leading edge From nose | 6.04 | m |
| Horizontal speed | 71 | m/s |
| Vertical speed | 0 | m/s |
| Density altitude | 1000 | m |
| ISA atmosphere | - | - |
| Rotor Lift | 430,000 | N |
| Wing Lift | 95,000 | N |
| Hover Lift@0m<br>No horizontal speed | 280,000 | N |

As it can be seen from Table-1, the penalty in hover is only 5,000N or 2% of the total lift available. This value is within the simulation approximations. The additional free lift in cruise s 95,000N, approximately 25% of the available lift from the rotors. Far more interesting is the torque necessary to keep the helicopter levelled in cruise. In this condition the collective pitch is reduced from 4 degrees for the unwinged helicopter [1] to 1 degree of the winged CH47. In this conditions the sum of two rotor torques nearly halves passing from 506,000 Nm (wingless with 4-degree pitch) down to 247,000 Nm (winged with 1-degree pitch). In this condition it is possible to shut down an engine like it was done on cruising for the Gloster Meteor WWII jet. Therefore, is possible to double the operational range of the helicopter.

**Additional weight considerations**

The manufacturing technology of the additional wing is similar to the one of the rotor blade. A good way to obtain a reasonable weight for the new wings can start from blade data. Carbon fiber rotor blades are manufactured with fully stressed carbon-fiber-skin tape-wounded around a foam core. Additional elements can be added in the core like sandwich structures and spars. For example, the weight of a Blackhawk rotor blade is approximately 114 kg. This blade has a length of approximately 16m with a chord of 0.5 m. The blades surface density is approximately 14.5 kg/m$^2$. Our wing for the CH47 has a chord of 1m and a length (span) of 15.7m. Therefore, its weight will be approximately 223 kg. This is less than 1/1, 000 of Chinook MTOW (Maximum Take Off Weight).

## CONCLUSIONS

The tandem rotor configuration is particularly convenient for the lift-compound approach in helicopters. In fact, the additional wing is positioned between the two rotors in an area that is marginally interested by the vertical flow in vertical flight. On the contrary, in horizontal flight, the airflow accelerated by the frontal rotor directly invest the wing improving its lift. A very thin wing with a short chord and a relatively large span can be manufactured with the same technology of the rotor blades. If this wing is fixed without control surfaces the additional weight can be extremely limited. A concave-convex high lift airfoil can be used. This airfoil is relatively stiff due to the large bending moment of inertia. A skin stressed structure can be used for the additional wing to obtain also a large torsional stiffness. This lightweight wing can be installed on the helicopter when required and it can be optimized to a defined flight condition. Its weight is less than 1/1,000 of the MTOW. In our case the optimization was performed for cruise. In this condition the collective pitch is reduced from 4 degrees for the unwinged helicopter [1] to 1 degree of the winged CH47. In this conditions the sum of two rotor torques nearly halves passing from 506, 000 Nm (wingless with 4-degree pitch) down to 247, 000 Nm (winged with 1-degree pitch). Theoretically it is possible to shut down an engine like it was done on cruising for the Gloster Meteor WWII jet. Therefore, is possible to double the operational range of the helicopter. This result is impressive for ferrying and long range passenger transport operations, where load capacity can be fully exploited only by increasing the fuel load. In this case a helicopter like the Chinook can perform long range missions with a significant increase in operational capability.

**Symbols**

| Description | Symbol | Unit |
|---|---|---|
| R | Rotor radius | m |
| $C_{wing}$ | Wing chord | m |
| $d_{rw}$ | Distance between rotor and wing | m |
| $X,X_1,X_2$ | Angles (see figure 4) | rad |
| i | Wing incidence on horizontal line | rad |
| $\alpha$ | Airflow angle of attack | rad |
| $\alpha_{TPP}$ | TPP angle | rad |
| $\alpha_{eff}$ | wing angle of attack | rad |
| $v_\infty$ | Helicopter horizontal velocity | m/s |
| w | Helicopter vertical velocity | m/s |

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