

Airbus AI-PX7 CROR Design Features and Aerodynamics

Camil A. Negulescu

Airbus Operations SAS, Toulouse, France

ABSTRACT

The renewed interest in the fuel efficient and low CO₂ emission CROR (contra-rotating open rotor) propulsion system for future commercial aircrafts has recently led to a series of isolated and installed CROR wind tunnel test campaigns performed in close collaboration between Airbus and the engine manufacturers. These tests aim at better understanding the potentials and limitations of the CROR configuration, as well as at generating reference data for the development and calibration of numerical tools for both industry and research centers. One of these tested CROR concepts is the AI-PX7 CROR propeller designed by Airbus.

In this context, this paper presents multidisciplinary design features of modern high-speed contra-rotating propellers for commercial aircrafts. The influence of main CROR design parameters like blade number, propeller tip speed, rotor diameter, etc. on the propeller aerodynamics, acoustics and structures is described. Moreover, CROR blade shapes aerodynamic, acoustic and structural design considerations, like blade loading and blade sweep distributions are exposed.

Finally, the design of the Airbus AI-PX7 CROR propeller is presented, as well as a steady-state and unsteady CFD analysis of the AI-PX7 CROR propeller aerodynamics.

CITATION: Negulescu, C., "Airbus AI-PX7 CROR Design Features and Aerodynamics," *SAE Int. J. Aerosp.* 6(2):2013, doi:10.4271/2013-01-2245.

INTRODUCTION

The rapid growth of aircraft fuel prices over the past 20 years has stimulated a series of studies of propeller propulsion systems for commercial aircrafts. Block fuel benefits of 20 to 35% are expected by the use of modern high-speed turboprops, with the highest fuel savings achieved by the CROR (contra-rotating open rotor) technology. Besides pure efficiency objectives, advanced high-speed propeller designs have nowadays also to attain aggressive noise reduction goals.

Actually, whereas the fan blades of a turbofan engine are ducted by the nacelle, the propeller blades of an open rotor engine are directly exposed to the aircraft flowfield and its inhomogeneities and so to an environment which is favourable for noise and vibrations generation. Likewise, from an aerodynamic point of view, a non-uniform propeller flowfield requires a robust propeller design and the mastering of propeller in-plane 1P efforts. It is therefore of major importance for the airframer to understand, characterize and adapt, together with the engine manufacturer, the behavior of the propeller in the aircraft flowfield. The design of the Airbus AI-PX7 CROR propeller, its numerical simulation and

wind tunnel testing are therefore important milestones for Airbus towards the development of the overall maturity of the CROR aircraft configuration.

The Airbus CROR propeller AI-PX7 (Fig. 1), which represents a pusher CROR designed for a rear-fuselage installation on a future notional commercial aircraft, was designed at the Airbus aerodynamic design office in Toulouse in 2009. The AI-PX7 CROR design will permit to test and assess the aerodynamic and aero-acoustic isolated and installed CROR performances, as well as the CROR's impact on the A/C (aircraft) performances and handling qualities. Wind tunnel tests are currently performed on different A/C models at different scales. Moreover, the Airbus AI-PX7 CROR geometry and part of the wind tunnel test results are shared with the European aeronautic research and industrial partners in the frame of the Clean Sky JTI project for assessment and calibration of aerodynamic and aero-acoustic numerical simulation tools.

This paper focuses on the design of the Airbus AI-PX7 CROR propeller based on multi-disciplinary design criteria and its aerodynamic numerical validation.

Multidisciplinary design features of modern high-speed contra-rotating propellers for commercial aircrafts are

presented. The influence of main CROR design parameters like blade number, propeller tip speed, rotor diameter, etc. on the propeller aerodynamics, acoustics and structures is described. Moreover, CROR blade shapes aerodynamic, acoustic and structural design considerations, like blade loading and blade sweep distributions, are exposed.

Finally, the design of the Airbus AI-PX7 CROR propeller is presented, as well as a steady-state and unsteady CFD analysis of the AI-PX7 CROR propeller aerodynamics.

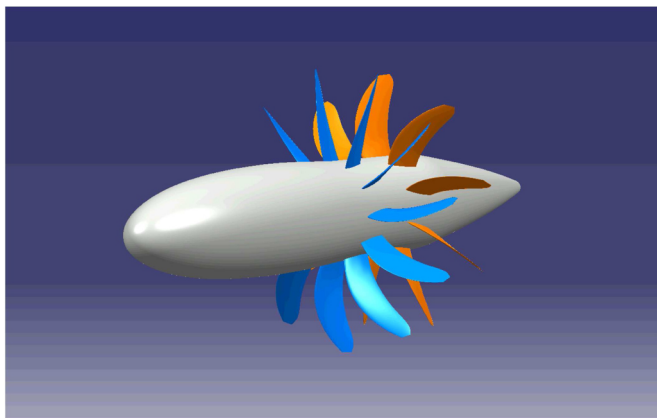


Figure 1. AI-PX7 CROR propeller mounted on a dummy nacelle.

DESIGN CONDITIONS

As mentioned above, multidisciplinary design aspects for CROR propellers for commercial aircraft will be presented in the following sections. The exposed design considerations are general and may be applied for civil or military contra-rotating propeller propulsion systems of different type of missions. Nevertheless, we will focus here on high speed contra-rotating propellers of 14.000-20.000 engine shp, flying at Mach=0.7–0.8 and at 31.000–41.000ft altitude adapted for a future CROR notional commercial aircraft.

The exact design points considered for the Airbus AI-PX7 CROR propeller, as well as its performance objectives, are listed in [table 1](#). The design is performed as a compromise between cruise and take-off aerodynamic and aero-acoustic design considerations.

Table 1. Airbus AI-PX7 CROR propeller design conditions.

Design point	Flight Conditions	Propeller design thrust	Efficiency target
Cruise	M=0.75 Alt=35kft ISA+0°K	4250 lbf (18905N)	>85 %
Max Take-Off	M=0.2 Alt=0kft ISA+15°K	24229 lbf (107775N)	>60 %

MAIN CROR DESIGN PARAMETERS AND THEIR IMPACT ON A MULTIDISCIPLINARY LEVEL

In the following sections the impact of the main design parameters of a CROR propeller on a multidisciplinary level are described. Moreover, design criteria for the choice of these parameters are given. The main design parameters of the Airbus AI-PX7 CROR propeller are finally exposed.

CROR Installation & Pusher/Puller Propeller Configuration

Before specifying the main design parameters of the CROR propeller, the airframer has to decide on the best mission suited CROR-to-Aircraft installation concept. Without looking at extravagant engine installation concepts, CROR engines can generally be mounted on the wing or on the rear fuselage with both puller and pusher propeller arrangements. We will focus in this paragraph on the two currently investigated installation concepts, i.e. the wing-mounted puller and the rear fuselage pylon-mounted pusher concepts, and give insight into multidisciplinary aircraft installation and turboprop architecture considerations. [Figure 2](#) and [3](#) show two examples of these two installation concepts.



Figure 2. AN-70 wing-mounted puller CROR.



Figure 3. Airbus Z08 A/C rear fuselage pusher CROR wind tunnel model

The wing-mounted puller concept has higher challenges to face in terms of cabin and community noise emissions. Indeed, the wing-mounted propellers radiate directly the noise to the cabin which is crossed by the propeller planes. This is not the case for the rear fuselage pylon-mounted pusher where the propellers are situated just after the rear-end of the cabin, thus making this concept more interesting from a cabin noise point of view. Furthermore, wing-mounted propellers see a higher local propeller incidence due to the wing up-wash, whereas on the contrary the rear fuselage pusher sees a reduced local incidence due to the wing down-wash. As propeller incidence has a direct impact on propeller tonal noise, the latest configuration has also potentially lower community noise emissions at take-off and landing condition. Surely it is true that the rear fuselage pusher propeller has an additional source of noise and vibrations, as the turboprop pylon wake is ingested by the propeller which is placed downstream of the pylon. Nevertheless, the effect of the pylon wake can be significantly reduced, at least at take-off and landing conditions, through the pylon trailing edge blowing technique [1].

From a propeller performance point of view, higher propeller efficiencies are attainable with the wing-mounted puller concept. Actually, due to nacelle and wing blockage the propeller sees lower local velocities in comparison to the rear fuselage pusher propeller which is placed in the nacelle overspeed region. Also, a higher propeller diameter can be specified for wing-mounted propellers increasing furthermore the propeller efficiency.

From an aircraft performance point of view it is more difficult to state. Surely, the rear fuselage pylon-mounted pusher propeller may potentially have less installation and slipstream drag than the wing-mounted puller propeller, but an accurate study is needed in order to finally state. One has also to keep in mind that the propellers of wing-mounted puller concepts may blow the suction side of the wing, so that less wing area is needed in order to generate the required lift, reducing thus the aircraft drag.

Finally, in terms of aircraft flight mechanics, several important aspects have to be considered. First, the higher local angle of attack seen by the wing-mounted puller propeller generates higher propeller in-plane efforts (1P efforts). These efforts impact the stability and trimming of the aircraft and have to be taken into account when designing the horizontal and vertical tail planes. Secondly, the rear fuselage pusher propeller concept has, due to its rear engine positioning, a more important centre of gravity displacement as fuel is burned during the flight. This will afford a more complicated trimming of the aircraft and potentially a heavier and aerodynamically less optimized horizontal tail plane. Finally, it has to be ensured for the rear fuselage pusher propeller concept that during the reverse condition at landing the controllability of the aircraft is not affected. In fact, the propeller planes are placed just upstream of the vertical tail plane and may so affect the vertical tail plane aerodynamics under reverse conditions.

From an engine architecture point of view the puller turboprop/CROR configuration is the more conventional configuration with proven technologies and lower risks. The majority of past and present turboprops are pullers. Fig. 4 displays a view of the Progress D27 puller CROR (14.000shp) of the AN-70 transporter aircraft. The turbomachinery is mounted in line with the contra-rotating propeller (8+6 blades). Other particularities of this concept are the use of a planetary gearbox and an annular inlet duct.

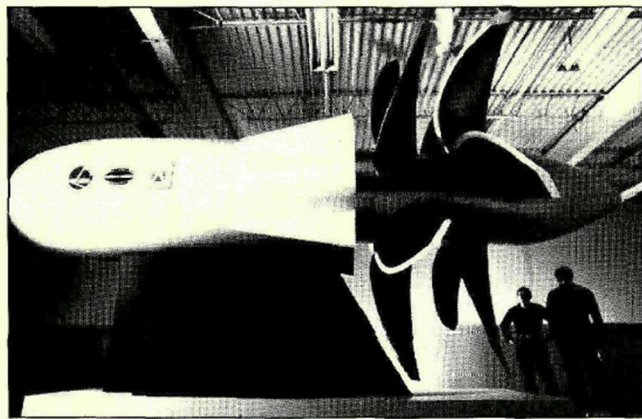


Figure 4. Progress D27 puller CROR

Turboprop/CROR pusher configurations are more challenging concepts due to the hot gases exhaust issue. In fact, the hot gases are either expelled upstream of the propeller plane (cf. PW/Allison 578DX geared propfan Fig. 5 [2] and Piaggio P180 Avanti PW Canada PT6 turboprop) or the hot gases are expelled through the rotating propeller root annulus (cf. PW/Allison 80's final geared propfan version 578E, Fig. 6 [3]). In the first case, an additional source of noise is created. Moreover, the propeller blades' inboard part works in the hot exhaust gases environment (700-850°K). Propeller blades have therefore to be protected from high temperatures, thus increasing blade mass and cost. In the second case, the hot exhaust gases pass in the vicinity of the gearbox, pitch change mechanism and propeller bearings, which have therefore to be protected from hot gases leakage. This may turn to be challenging and maintenance costs may be increased.

The reference CROR installation concept used at the moment by Airbus for CROR propulsion system to aircraft integrated studies is the rear-fuselage pusher configuration with hot gases expelled through the rotating propeller root annulus. As exposed above, this is mainly due to its better cabin comfort and lower community noise. This concept is in the mean time a challenging concept, as it requires tackling potential aircraft trimming, reverse controllability and pylon blowing issues. Also, the engine manufacturer has to face

higher challenges with the CROR pusher concept than with the more classical CROR puller concept.

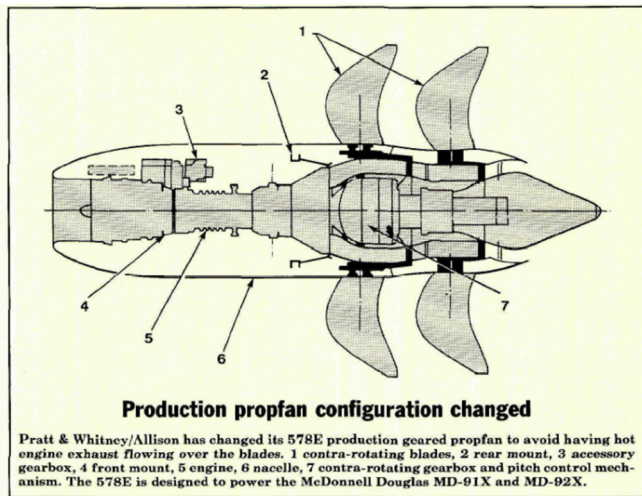


The Allison/Pratt & Whitney Model 578DX propfan demonstrator engine will fly on a McDonnell Douglas MD-80 late next year

Figure 5. PW/Allison 578DX geared propfan [2]

The design of the Airbus CROR propeller AI-PX7 is consequently based on the rear fuselage pylon-mounted pusher configuration with hot exhaust gases expelled through the rotating propeller root annulus.

Up to now, the pusher rear-fuselage CROR installation concept was flight-tested by American engine manufacturers during the 80's contra-rotating turboprop powered civil aircraft programs. Russians contra-rotating turboprops are mainly puller wing-mounted configurations.



Production propfan configuration changed

Pratt & Whitney/Allison has changed its 578E production geared propfan to avoid having hot engine exhaust flowing over the blades. 1 contra-rotating blades, 2 rear mount, 3 accessory gearbox, 4 front mount, 5 engine, 6 nacelle, 7 contra-rotating gearbox and pitch control mechanism. The 578E is designed to power the McDonnell Douglas MD-91X and MD-92X.

Figure 6. PW/Allison 578E geared propfan [3]

Propeller Hub-to-Tip Ratio

At fixed propeller diameter, a low propeller hub-to-tip ratio increases the effective propeller annular surface, diminishing thus induced velocities and increasing therefore efficiency.

The propeller hub-to-tip ratio is generally fixed by the CROR configuration. For a puller configuration, the hub-to-tip ratio can be kept low ($D_{hub}/D_{tip} \sim 0.2-0.3$). Its value depends on the number of blades that have to be integrated in the spinner. For a pusher configuration we have rather $D_{hub}/D_{tip} \sim 0.25-0.40$ depending on the gearbox and exhaust unit architecture. Indeed, if hot gases are expelled through the propeller root annulus and furthermore the propeller gearbox is integrated in the blade hub, the hub-to-tip ratio is high ($0.35-0.4$). Such a configuration is depicted in figure 6 and represents PW/Allison 80's final geared propfan version [3]. In the case where the exhaust gases are expelled upstream of the propeller plan (Fig. 5), the hub-to-tip ratio is lower : $D_{hub}/D_{tip} \sim 0.25-0.3$.

For the Airbus pusher CROR propeller AI-PX7, with the hot gases exhaust through the propeller root, the propeller hub-to-tip ratio is set at $D_{hub}/D_{tip}=0.35$.

Blade Number and Distribution

The blade number has an important impact on the aerodynamics, acoustics and structures of the propeller. The activity factor of a propeller AFP, required to absorb the takeoff thrust and to work at the design lift coefficient at cruise conditions, can be achieved by a small number of blades with a large chord or by a high blade number with a small chord.

For aerodynamic and acoustic reasons a high number of blades is preferred. Increasing the blade number (at constant propeller activity factor AFP) reduces blade tip losses (as the blade aspect ratio is increased), therefore increasing efficiency. Noise is reduced by shifting the noise to higher frequencies, reducing thus the perceived noise and moreover by increasing the propeller blades' phase cancellation. From a structural point of view few blades with a large chord are preferred in order to keep stresses low and to lower the flutter risk. On the other side, at constant propeller activity factor AFP, a propeller with few blades with large chords is heavier, increasing thus the CROR weight.

Listing the advantages and disadvantages of a high number of blades, we get :

Advantages :

- Efficiency increase

- Noise reduction

- Weight reduction

Inconvenient :

- Higher blade stresses

- Increased flutter risk

- Complex hub / pitch change mechanism

- Higher CROR acquisition & maintenance costs

Therefore, the blade number of a CROR or a turboprop in general has to be adjusted in order to take as much as possible

benefit of the aerodynamic and acoustic advantages of a high blade number without deteriorating the structural characteristics of the propeller and increasing the complexity of the whole system.

Existing modern single-rotating or contra-rotating puller open rotor engines like A400M's TP400 engine or AN-70's D27 engine have up to 8 blades per rotor row. For future designs up to 10 blades per rotor row should be manageable with structurally well-designed spinner and blades. For pusher open rotors with the exhaust gases flow through the blade roots even higher blade numbers are possible, as GE's UDF CROR 10×8 blade concept that was tested in the 80's showed. In the same way, a future CROR pusher may go up to 12 blades per rotor row.

Furthermore, in the case of contra-rotating propellers the front/rear rotor blade distribution is also very important. At equal front/rear rotor rpm, equal front/rear rotor blade numbers have to be avoided from an acoustic point of view. Indeed, propeller noise consists of harmonic noise superimposed on broadband noise. Harmonic noise dominates propeller noise and occurs for a CROR at integer multiples of the front and rear rotor blade passage frequencies BPF1 and BPF2 and their linear combination. Thus, front/rear rotor alone tones are emitted at integer multiples of the corresponding rotor fundamental frequency ($m \cdot \text{BPF1}$ for the front rotor, respectively $n \cdot \text{BPF2}$ for the rear rotor), while interaction noise occurs at combinations of the rotors' fundamental frequencies ($k \cdot \text{BPF1} + l \cdot \text{BPF2}$). For equal front/rear rotor blade numbers (at equal front/rear rotor rpm) the harmonic tones of the rear rotor, as well as the interaction tones, are produced at the same frequencies as those of the front rotor (Fig. 7 [4]). On the contrary, for unequal blade numbers noise is spread over different frequencies (Fig. 8 [4]) changing thus the frequency envelope shape and diminishing the overall sound pressure level (see also [4, 5]).

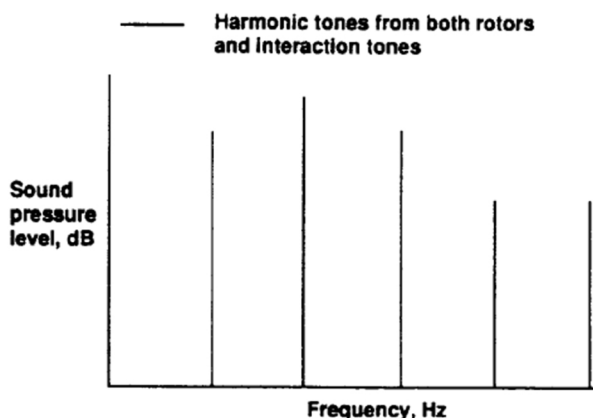


Figure 7. Harmonic and interaction tones, $n \times n$ CROR [4]

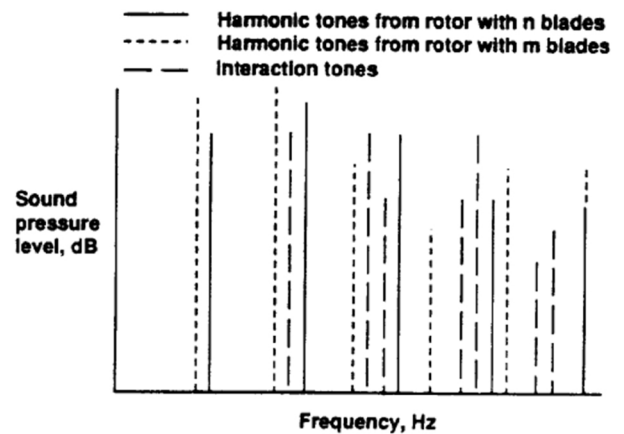


Figure 8. Harmonic and interaction tones, $m \times n$ CROR [4]

From a noise point of view it is therefore suitable to have unequal front/rear rotor CROR blade numbers with no common multiple factor. A difference of 2-3 blades for a total of 14-20 blades is suggested. A difference of more than 3 blades would have a negative impact on the propeller aerodynamic efficiency. Actually, while operating at realistic front/rear rotor power and momentum ratios ($\sim 55/45$), the blades of the rotor with less blades would be too highly loaded.

For the Airbus pusher CROR AI-PX7 having a propeller hub-to-tip ratio of 0.35, a total blade number of 20 blades and a 11×9 front-rear rotor distribution has been chosen taking into account aerodynamic, acoustic, structural and space allocation concerns.

Propeller Diameter

The propeller diameter is chosen in order to fulfil aerodynamic and acoustic performance objectives while considering structural, weight and space allocation issues. Thus, cruise performance and take-off maximum thrust requirements must be reached by the selected diameter, as well as maximum allowable cabin and community noise levels not exceeded.

The impact of the disk power loading, which is expressed as shaft horsepower divided by the square of the propeller diameter, i.e. SHP/D^2 , on the propeller cruise efficiency is depicted in figure 9 [6] for single- and contra-rotating propellers with variable blade numbers. Reducing the disk power loading (i.e. increasing the diameter) increases efficiency as induced velocities are reduced. At equal power loading, contra-rotating propellers have much higher efficiencies due to smaller swirl losses as a consequence of the swirl recovery by the contra-rotating rear propeller. Also, the efficiency of contra-rotating propellers is less sensitive to the power loading. Indeed, contra-rotating propellers can be quite highly loaded without an important efficiency loss. Finally, as already stated, increasing the blade number

increases efficiency, as blade tip losses are reduced. A higher diameter can also absorb more power at take-off and generate therefore more take-off thrust.

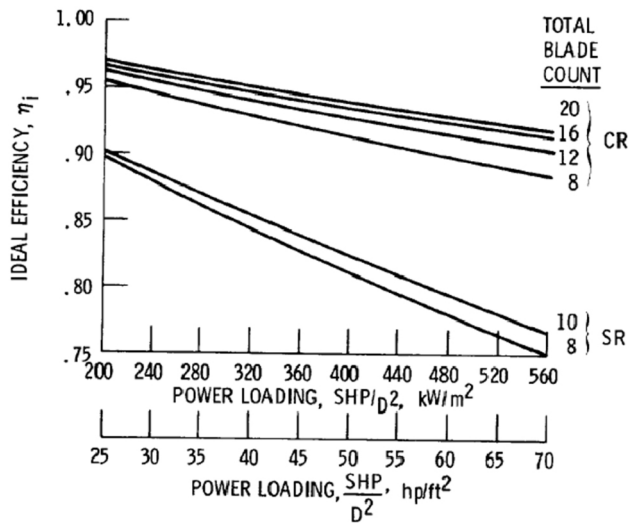


Figure 9. Single- and contra-rotating propeller ideal efficiency: $M=0.8$, $Alt=35,000ft$, $tip\ speed=800ft/s$ [6]

From an acoustic point of view a higher diameter is also preferable. The local blade load of a propeller with a low disk power loading is reduced, thus reducing the propeller harmonic loading noise. Moreover, at high speed conditions the blade shock intensity is thus also reduced, lowering quadrupole noise sources.

On the other side a high propeller diameter impacts negatively the weight of the propulsion system. A propeller with a large diameter is heavier. Moreover, when increasing the diameter the rpm has to be reduced in order to keep the blade tip speed at aerodynamically and acoustically acceptable values. A lower rpm means a higher propeller momentum and therefore a more robust and heavier gearbox. Finally, a heavier propeller and a heavier propeller gearbox require reinforced and heavier engine mounts. Therefore, the global weight of the propulsion system is increased by a snow ball effect.

The propeller diameter is also limited by the CROR-to-aircraft installation concept. For a wing-mounted CROR the propeller size is limited by the ground clearance and in the case of more than one engine per wing by the propeller-to-propeller and propeller-to-fuselage clearance. For a rear-fuselage installation concept the diameter is limited by the propeller-to-fuselage clearance.

Nowadays, turboprops have maximum diameters of up to 18ft (TU-95 NK-12: 18ft, A400M TP400: 17.5ft, AN-70 D27: 14,76ft) for wing-mounted engine configurations. For rear-fuselage mounted turboprops the diameter has to be lower (e.g.: GE36' UDF installed on a MD-80 demonstrator: 11ft) but diameters of 13-14ft are realistic.

For the Airbus pusher CROR propeller AI-PX7 in the rear-fuselage configuration a propeller diameter of 14ft has

been chosen in order to take as much as possible advantage of the aerodynamic and acoustic benefits of a large diameter with an acceptable structural and weight impact.

Rear Rotor Cropping & Rotor Disk Spacing

Compared to a single-rotating propeller, a contra-rotating propeller has an additional source of noise, the rotor-to-rotor interaction noise. Indeed, the wakes and tip vortices leaving the front rotor blades impact the rear rotor and generate on the rear rotor blades sequential lift pulses and thus unsteady-loading noise. Also, the potential fields around the front and rear rotor blades can interact with each other and generate in the same way unsteady-loading noise. The interaction noise is the dominant source of noise at low speed conditions and is one of the main drawbacks of the contra-rotating propeller propulsion system.

For small rotor spacings, the interaction noise is dominated by the interaction of the front rotor wakes with the rear rotor and by the interactions of the front and rear rotor potential fields. For higher rotor spacings, the interaction noise is dominated by the front rotor tip vortices interaction with the rear rotor. Actually, the viscous wakes degenerate more rapidly downstream than the highly energetic tip vortices do [7].

This paragraph will present two ways for reducing the rotor-to-rotor interaction noise : cropping the rear rotor diameter and spacing the rotor disks. As mentioned above, interaction noise is a dominant noise source at low speed conditions. The here presented measures will consequently be tailored for low speed conditions.

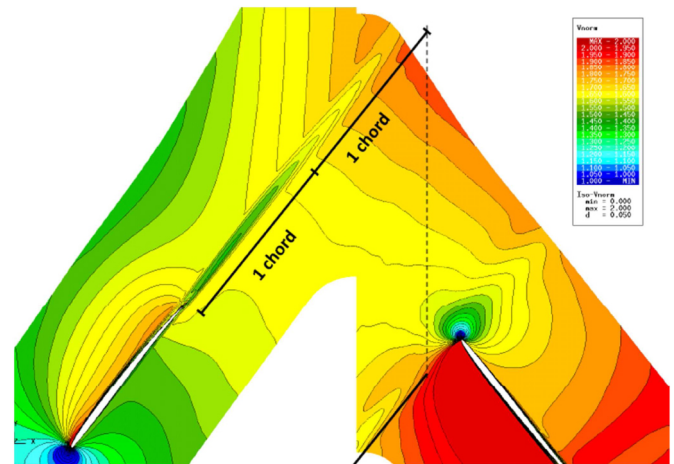


Figure 10. AI-PX7 CROR front rotor wake evolution at takeoff conditions (chorochronic high density mesh computation)

In order to reduce the interaction noise due to the impact of the front rotor wakes with the rear rotor, the rotor disk spacing has to be significant. As a hand rule, one can suppose that the front blades' wakes have lost an important part of their velocity deficit two chords downstream of the front rotor blades' trailing edges (Fig. 10) [see also [8] for the