The Aeronautical Journal (2023), **127**, pp. 699–736
doi:10.1017/aer.2022.92

REGULAR PAPER

Historical development of the coaxial contra-rotating propeller

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Received: 7 July 2022; **Revised:** 30 September 2022; **Accepted:** 12 October 2022

Keywords: Contra-rotating propeller; open rotors; propulsion; technology history

Abstract

We review the development of the contra-rotating propellers from the origins to the present. Initially, these systems were proposed to increase speed, then to increase propulsive efficiency, and thus reduce fuel burn. Ultimately, they hit another environmental limit: too much noise. Acoustics has been in fact the main focus of the development in the past 30 years. Pioneering work done across countries demonstrated several unique features of this propulsor. Various embodiments are available, namely contra-rotating, counter-rotating, co-axial, tandem, open rotor and prop-fans, collectively named contra-rotating propellers. This review only considers concepts that have been applied to real aircraft, prototypes that are known to have been flight tested (about 70 vehicles), or representative laboratory models. Five classifications are proposed: pioneers (before 1940), golden years (1940–1950), Western airplanes (1950s onwards), Soviet-Russian airplanes (1950s onwards) and modern developments (1980s onwards). Selected experimental aircraft and laboratory concepts are mentioned, where these appear to advance the state-of-the-art. Power plants evolved from internal combustion engines to the modern gas turbine engines requiring new solutions. Engine layouts and propulsion configurations are analysed where appropriate. It is concluded that propulsive efficiency can only be achieved at a cost of multiple engineering problems, some of which remain unsolved.

Nomenclature

AEW	airborne early warning
CRP	any contra- or counter-rotating propeller
EPNL	effective perceived noise level
IC	internal-combustion (piston) engine
SPL	sound pressure level
SRP	single rotation propeller
TP	turboprop
rpm	rounds-per-minute
-p	contra-rotating propeller – pusher
-t	contra-rotating propeller – tractor
b	blade span
c	blade chord
C_P, C_Q, C_T	power, torque, thrust coefficient
D	propeller diameter
J	advance ratio
M	Mach number
N	number of distinct CRP
N_b	blade count per blade row
P	power
Q	torque

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R	propeller radius
T	thrust
V	flight speed
W_p	propeller weight
x	distance between propeller disks
η	propulsive efficiency
σ	propeller solidity, $N_b c/\pi R$
θ	collective pitch angle
Ω	angular speed
$[.]_{1,2}$	fore and aft propeller (or blade row)

1.0 Introduction

The contra-rotating propellers are some of the oldest propulsion concepts in aeronautics. They can be traced back to at least a 1907 patent by Lanchester. They were previously known for applications in marine environments, including torpedoes, so the idea was not completely new. Various names have been proposed, such as duplex airscrews, contra-props, dual-rotation propellers, counter-rotating open rotors, tandem propellers, prop-fans and more. The term *airscrew* was popular up to the 1940s, but it was then supplanted by the term *propeller*. Old patent literature (1930s) refers to *tandem* as equivalent to dual rotation or contra-rotation. We will use the general acronym CRP for all contra-rotating propellers, although there can be substantial differences in the mechanical assembly, the engine architecture, the drive train and the governor systems; these differences are pointed out in specific cases.

Their common feature is that two closely spaced propellers rotate in the opposite direction around the same axis, with the purpose of increasing net thrust and overall propulsion efficiency at higher speed than a single propeller. Two propellers rotating in the opposite direction on *different shafts* are called *counter-rotating* [1]. These latter embodiments are not considered here. Frustratingly, most of the recent technical literature does not differentiate between these two concepts, and the term *counter-rotating propeller* seems to be prevalent, regardless of the mechanical construction.

The CRP concept – elegant in principle – is fraught with several technological difficulties and unproven benefits that have limited its use to relatively few airplanes, mostly military or experimental test beds. These drawbacks include mechanical complexity, manufacturing costs, weight increase, vibrations, whirl flutter, and noise. Alongside a delineation of the historical development, we highlight key technical issues such as speed, propulsive efficiency and torque delivery. We examine concepts that are known to have flown or tested as prototypes, and discard most of the patent literature (thousands of registrations) that has not been fully demonstrated.

The patent literature is a true minefield: Many patents are tactical operations aimed at stifling competition. Cross-referencing is generally poor, and evidence of originality in comparison with the state-of-the-art is difficult to demonstrate. The terms "*Improvement in or relating to*. . ." are often used.

A search in patent databases shows that the number of patents has been increasing sharply since 2010, well above a previous peak reached in the 1990s. Safran Aircraft Engines and United Technologies have been awarded most patents in recent years for "counter rotating open rotors". For older designs, detailed diagrams are available in *Flight Magazine* drawings [2], patents [3, 4], company brochures [5], and papers [6].

The literature on our subject is a mix of technical publications by the industry (including operating manuals), professional magazines, official and unofficial photographs, regulatory documents such as type certificates, technical papers, books, and a myriad of photographs and videos available on the Internet.

A historical review is important to identify trends, successful ideas, errors of judgement, and finally assess whether – after one hundred years of trying – the contra-rotating propeller is still the future of aeronautical propulsion. Considerable sums have been invested on this technology in the past decade alone. Once a project decision has been taken and funds committed, there is no turning back.

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We estimate that about 70 historical aircraft have been powered by CRP, some of which were one-off and some incomplete test beds. About 15 vehicles entered production and served for at least a few years; a dozen flying test beds are known; at least 5 airplanes served in war zones or combat operations. Only one aircraft provided passenger services: the Tupolev Tu-114. A summary of our findings is reported in the Supplementary Materials.

Before 1940, engineering knowledge was derived by trial, engineering judgement, daring projects, and scant consideration of flight safety. The first question to ask is: Why would anyone want to use contra-rotating propellers? The main advantages that have been named include the following:

1. A CRP offers propulsive efficiency gains compared to a conventional propeller, particularly at high speeds. These benefits would suit a multi-engine long-range transport airplane. Higher propulsive efficiency would translate into longer range and lower fuel consumption, although this is disputed.
2. A CRP applied as a single propeller eliminates torque reaction. This has some advantages; in the case of fixed-wing airplanes, it eliminates a tendency to roll at high torque outputs and low speeds, when there is little dynamic pressure on the wings, no aerodynamic control authority and the propeller mass is relatively large; hence, the CRP increases lateral stability. This feature would suit a single-propeller high-powered airplane designed for STOL manoeuvres, particularly on aircraft carriers, where space was limited and wings had to be folded/stowed.
3. For the case described above, the CRP provides benefits at high angle-of-attack, such as steep climb. In this instance, a single propeller suffers asymmetric blade loading effect (*P-factor*). A descending blade has a lower apparent inflow angle than the ascending blade. This asymmetry forces the airplane to yaw [7]. In high-power climb, both roll and yaw can occur, which would be prevented with a CRP. Side-slip and rudder deflection may counteract the P-factor, but only at full speed.
4. A CRP provides high torque absorption with a relatively small-diameter propeller. A smaller diameter also reduces the tip Mach numbers, reduces the amount of ground clearance, and hence requires shorter landing gears. This feature would possibly reduces structural weight.

Points 2 and 3 in this list are no longer relevant; they are obsolete requirements.

2.0 Propeller layout

Since at least the 1940s [2, 8] there has been a distinction between *contra-rotating* and *coaxial* propellers. Blades on one rotating disk are a *blade row*. A contra-rotating propeller is a unit made of two blade rows arranged to rotate at the same speed in opposite directions. The two blade rows are linked to each other via a common drive shaft. Pitching and feathering is controlled simultaneously, and there is a single propeller governor. Normally, this arrangement is driven by a single engine, such as was the case of the Rolls-Royce *Griffon* 85 on the Spitfire Mk 22, or by twin engines, via a central gearbox.

Coaxial propellers are separate propeller units mounted on coaxial shafts, each driven by independent engines. This implies that pitching and feathering are independent. In principle, the two angular speeds can be different, one blade row can be stopped, feathered or folded. Experiments on CRP with a blade row locked or windmilling were carried out as early at 1945 [9], but there is no evidence that such a contraption was tried in flight.

The term *prop-fan* was presumably used for the first time in 1971 by Hamilton-Standard to define an *unducted turbofan* having the benefits of a turboprop/turboshaft engine with one or two rotors [10], which are either geared or direct-drive. The term *open rotor* is sometimes used in place of prop-fan. The main difference between a turboprop and a turboshaft is that in the latter case there is only minimal residual thrust from the exhausts; all the propulsive thrust is generated by the propeller blades.

Airplanes with back-to-back propellers which, although seemingly aligned, do not benefit from the close-spacing aerodynamic interference between rotor disks are not CRP. These systems are

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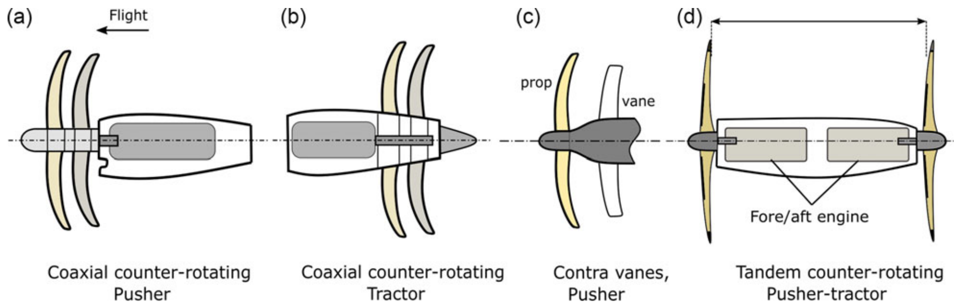

Figure 1. *Selection of CRP configurations.*

appropriately called *propellers in tandem*. A propeller mounted forward of the engine is defined as *pusher*; a propeller mounted aft is a tractor (or puller). A sketch displaying these configurations is shown in Fig. 1. Over the years, there have been designs with fore- and aft-mounted engines. Aft-mounted pusher propellers were preferable when the wing had large sweep. However, their perceived advantages of un-obstructed air intakes was offset by severe vibrations and the difficulty to divert the exhausts away from the blades. A tractor- versus pusher prop-fan installation analysis (weight, efficiency, operating costs) was published by Pratt & Whitney [11], and it was concluded, belatedly, that “there is no clear winner”.

As an alternative to the CRP, Betz [12] provided a theoretical justification for *contra vanes*, which had been tested earlier (1933) in the wind tunnel by Lesley [13]. This was a two-bladed prop with four-bladed contra vanes. The contra vanes can be used to recover at least some of the swirl. It was concluded that efficiency gains could be obtained, depending on the number of vanes, their diameter and their hub diameter. This concept did not win much support. However, CRP operating with the aft blade row locked works as a propeller with contra vanes and has been demonstrated to yield some propulsion benefits [14].

A series of wind tunnel tests were carried out at NACA during the War years; they culminated in a number of reports [15–17] exploring aerodynamic effects and comparisons with single-rotation propellers.

2.1 Gearboxes, drive shafts and systems

Gearboxes include reduction gear, contra-rotating gear, and planetary gear for pitch control. Considerable literature exists that shows all embodiments on gearboxes and drive trains, one example of which is shown in Fig. 2, for a Curtiss-Electric propeller: there are at least 16 different gears and 4 shafts with electric motor drive for pitch control. The blade shanks are at the top of the graph. A Curtiss patent [4] of that time showed unusual complexity, with hundreds of parts.

The propeller governor (and the *propeller electronic control* in modern propellers) is a speed control system that in its simplest embodiment consists of an rpm-sensing device connected to a pitch-control mechanism by means of hydraulic systems. Mechanical flyweights and springs have been used in the past. Electrical and magnetic control systems are more common today. There is a variety of governors, which are beyond the scope of this contribution.

An important innovation is attributed to Hamilton Standard with their *Superhydromatic* propellers. They were made of hollow steel, hence lighter, with rapid pitch-change mechanisms (up to 35 degrees/s), deemed essential for high-power manoeuvres, reversing and stopping on the ground [18]. The blades rotated on their axes by individual hydraulic vane motors housed within the open bore of each blade root. The hydraulic fuel supply was independent from the engine. Each blade row had its own pump and oil supply, which was believed to be appropriate, but failed spectacularly in at least one case, the Hughes XF-11.

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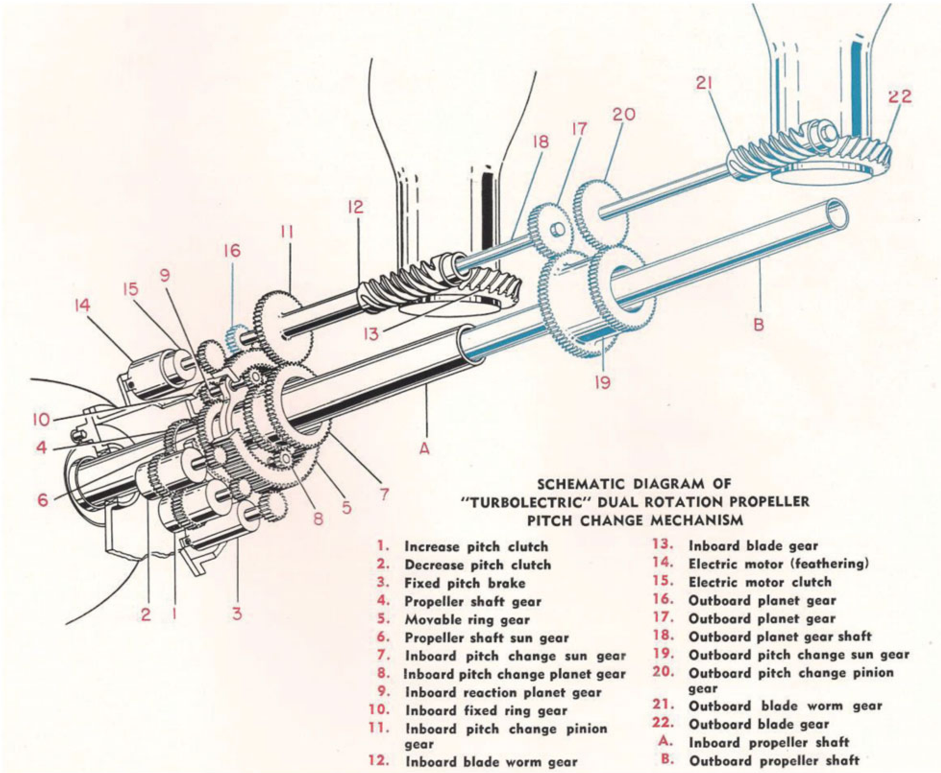

Figure 2. *Curtiss Electric dual-rotation propeller pitch control mechanism and relative description, Ref. [5].*

Hydraulic pitch control was available from de Havilland and Rotol, and it essentially consisted in using engine oil under high pressure to drive a central rack through the propeller axis.

Due to the structural loads at the shaft, their mechanical complexity involving hydraulic and electrical actuators, they are subject to stress and fatigue; for a long time they have been a weak link in the entire propulsion system. Gearbox failure contributed to the cancellation of some programmes (i.e. the Douglas A2D). A parametric analysis of weights, complexity and efficiency is provided in Ref. [19].

In some cases, long drive shafts are inevitable, i.e. CRP mounted on swept wings (Tupolev Tu-95, Tu-114), or aft-mounted pusher CRP (Northrop XB-35, Douglas XB-42). In other cases, the design choice was less fortunate i.e. the French Arsenal VB-10 (1944) had two coupled engines [20, 21]: One was placed at the nose and another one behind the pilot. Each engine drove a blade row that made up a contra-rotating propeller that could be driven independently. The front engine drove the aft propeller; the rear engine drove the fore propeller. It used a Latécoère 299A as a test bed, but there is no evidence that it flew. Similar engine architecture was on the Soviet Bohlkhovitinov *Spartak* and the Japanese Kawasaki Ki.64 (one engine forward and one aft of the cockpit). Long drive shafts were on the Koolhoven F.K.55, Convair XFY-1 *Pogo*, Lockheed XFV-1 *Salmon* [22], and Tupolev Tu-91 (all engines behind the cockpit).

Due to their complexity, modern propellers require their own certifications; the software control units must comply with the most stringent regulations. Achieving a new type certificate is a major undertaking that is often under estimated. An advisory note from the FAA [23] describes an acceptable method that may be used to demonstrate compliance to the propeller type certification requirements of *Title 14, Code of Federal Regulations, Part 35*. However, these regulations to do not apply to CRP, as stated in

Section 2.1.6 of said document, where it is reported that "*The complexity of a contra-rotating propeller has not been considered; therefore, additional requirements may need to be established.*" Terms of Reference published by the EASA [24], and agreed by the industry, highlight the difficulties of these new propulsors, and advise that they should be certified under engine regulations, with additional provisions to account for the characteristics of the open rotor. These provisions mention at least uncontained rotor failure and bird ingestion. No CRP is currently certified. Any remaining Russian CRP may follow domestic military certification.

2.2 Blade count

In his 1940 review, McCoy [25] stated that "it is possible that single-rotation propellers with more than four blades will never be commonly used." Reference [26] formulated the statement that "five blades is about the maximum number that can physically be accommodated in a single rotation hub". Five-bladed propellers already appeared in later models of the Supermarine Spitfire (1942–1948). Thus, up to the 1950s a further increase in blade count necessitated counter-rotating propellers. The first versions of the Lockheed C-130 had three-bladed Curtiss-Electric fully reversible propellers, which eventually became four-bladed Aeroproducts propellers [27] and currently six-bladed Dowty R391 [28, 29]; six-bladed propellers are now common, and eight-bladed propellers are also possible. These include the FH385/-6 propeller (Airbus A400M) and the Hamilton Sundstrand NP2000 (Lockheed C-130 upgrade). A few modern CRP prototypes have blade counts in double digits.

Increasing the blade count is an alternative to using contra-rotation propellers. A design blade loading T/σ can be achieved by controlling propeller solidity σ. For a given diameter, an increase in net thrust is accommodated by increasing the blade count or the blade chord, or both. A single-rotation prop-fan with several blades can absorb the same torque as low blade-count contra-rotating propeller. For example, the 8×6 CRP (Aerosila SV-27) of the Antonov An-70 powered by the Ivchenko-Progress D-27 engine delivers up to 10,380 kW, whilst the single-rotation propeller (eight-bladed Ratier-Figeac FH386) powered by TP400-D6 turboprops can deliver up to 8,250 kW with 91.6 kNm torque on the Airbus A400M.

2.3 Propeller parameters

It is important to clarify how the blades are counted, to avoid double counting. Each blade row has its own blade count, say N_1 and N_2. Therefore, the total number of blades is $N_1 \times N_2$. The confusion stems from the fact that early propulsion systems had the same number of blades, the same diameter and rotor solidity; however this is no longer the case. Thus, we define a diameter ratio D_1/D_2, a power split P_1/P_2, a torque split Q_1/Q_2, an angular speed ratio Ω_1/Ω_2, etc. Normalised axial separation x/D ranges from 0.1 to 0.2 for most CRP, except prop-fans, whose axial separations can be as large as 0.30, with hub-to-tip diameter ratios of 0.35–0.40.

The rotor solidity, $\sigma = N_b c/\pi R$, is calculated for each blade row, although there can be cases where the total number of blades is used if the blade rows are geometrically similar. A parameter that is sometimes used is the *activity factor*, which is a measure of the geometric width of a blade, and hence the load. The activity factor is calculated from the radial integration of the normalised chord $(c/D)^3$ via a multiplicating factor leading to values $\sim 10^2$; by contrast, we have $\sigma < 0.5$. It is not possible to evaluate the activity factor without detailed blade data. However, since it is proportional to the blade solidity, the latter parameter is used. Modern prop-fans have complex geometries with variable chord ($c/D \sim 0.15$) and short spans ($b/D \sim 0.4$–0.5).

It is common to have differential pitch settings of fore and aft blade rows. These settings have to be finely tuned in order to avoid vibrations, reduce noise and maximise propulsive efficiency. One example cited is that of the Supermarine *SeaFire* F.47 Rotol CRP [30], where the fore propeller was set at 20 degrees and the aft propeller at 23.5 degrees [31].

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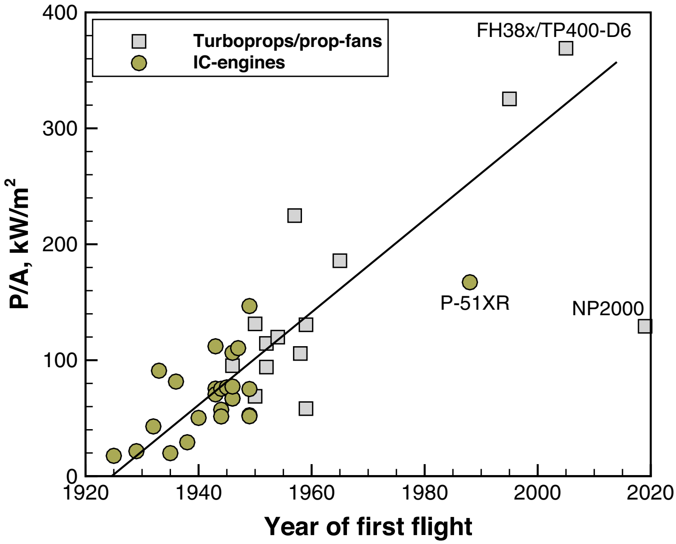

Figure 3. *Summary of CRP power loading.*

Other parameters include the net-thrust/disk area (T/A) or net-thrust/blade-area ($T/\sigma A$). Loading is also given as shaft-power/disk-area (P/A, measured in kW/m^2). The P/A ratio is a design constraint.

Values of P/A for modern prop-fans reach 400 kW/m^2, but exceed this limit in laboratory test models. A statistical analysis of this parameter is shown in Fig. 3. The data points are only approximate, and they rely on estimated power output at take-off, the mean diameter between the blade rows and equal distribution of power; however, this is not always correct. For counter-rotating propellers, it is assumed that each engine powers one blade row. For contra-rotating propellers where a single engine powers both rows, then the power is split equally. Aside from these caveats, there is no doubt that the blade loading has increased considerably over the years. The FH385/-6 with the Europrop TP400-D6 is a single-rotation propeller [32], but it has been added to the chart to demonstrate that highly loaded advanced propellers and prop-fans can provide as much power as a CRP. A graphic comparison among different propellers is sketched in Fig. 4.

2.4 Propeller blade design

The origins of propeller blade section design are unclear, but there is an interesting historical perspective provided by Bass [6] at Rotol, including CRP concepts and blade construction materials. Blade planforms were designed by quantitative guessing and then tested in the wind tunnel. Early tests by Durand and others at Stanford University from the late 1910s were aimed at defining optimal propeller performance. Propeller blade sections were characterised by flat lower surfaces (i.e. Clark Y), but there was no practical way of producing an "inverse design" that satisfied aerodynamic constraints. Tip speeds are always high, with helicoidal Mach numbers well in the transonic regime and bordering supersonic operation, with flight at Mach $M = 0.7$ to 0.8 and altitudes above 30,000 feet.

This problem was partially solved with the NACA 16-series airfoils [33], developed in the late 1930s for propeller applications, particularly in the outer sections that operate at transonic Mach numbers. These sections were used by Curtiss-Wright for their propellers in the late 1940s [34].

Propeller design was uncharted territory for a long time, and the thinking going into this initiative is better explained by Vincenti [35]. Due to the large number of design and operational parameters, performance was investigated either by trial and error or by parameter reduction with normalised quantities. In any case, propeller-engine-airframe integration was done on the basis of engineering experience.

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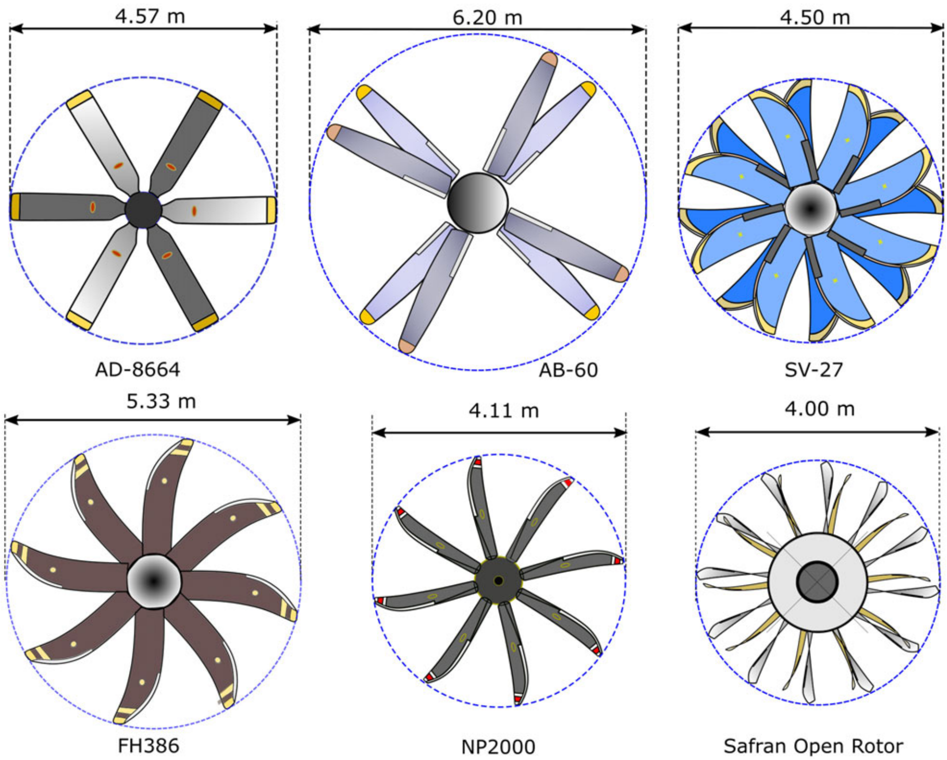

Figure 4. *Selection of CRP and SRP, including the Ratier-Figeac FH385/-6 (Airbus A400M), the Hamilton-Sundstrand NP2000 (Lockheed C-130H and P-3, Northrop Grumman E-2) and the Safran Open Rotor.*

In the UK, the Research Aircraft Establishment had a long term plan for developing high speed propeller blades from 1943 onwards and tested several propellers for Rotol and de Havilland. For example, MacDougall [36] shows results of tests on a de Havilland propeller with NACA 16-series sections.

An analysis of the Rotol CRP blade section of the fore blade of the Fairey *Gannet* at 47% radius indicated that the closest aerofoil was a NACA 16-series (Turnberg & Brown [14] at Hamilton Standard under a NASA contract), although an exact correlation could not be found. Furthermore, the aft blade had a larger chord ($\sim$ 1 cm) and relative thickness ($\sim$ 1%). Reference [37] asserts that the blades were Duralumin NACA 16-series. Fairhurst [38], Chief Engineer at Rotol, stated in 1956 that "at present, the best known aerofoil section is the NACA 16-series", although consideration was made for the NACA 65-xxx airfoils for inboard sections and double wedge geometries for high speed. The 16-series remained in use at Rotol at least until the development of the R212 propeller [39, 40] in the 1950s.

It is inferred, without definitive proof, that Rotol, de Havilland, Aeroproducts, and Curtiss-Wright used the NACA 16-series airfoils for their CRP designs. These airfoils are mentioned in the research reviewed at Curtiss-Wright [34], Rotol [38], de Havilland [26, 36] in the late 1940s and through the 1950s. This author found no information on Soviet aerofoil research of this period, but it is likely the Soviets managed to access Western research and used these airfoils as well. There is evidence of their use of the Clark Y airfoil (Ilyushin Il-2). Later research used unspecified TsAGI (Central Hydrodynamics Institute) aerofoil sections.

Aerofoil sections for CRP blades are supercritical or supersonic sections with thickness of 3–4% in the outboard regions, about 6–7% thick at 70% span, growing to about 30% relative thickness at the shank.

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Modern CRP, alongside the single-rotation propellers, are designed to operate at virtually constant rpm, although some have dual-speed options (take-off and cruise). Constant speed is always interpreted as a ± few rpm. Variable pitch is the norm on most propellers; some have wide range of pitch angles so that they can reverse the direction of the thrust (*fully reversible)*. In the early years, the use of variable pitch in flight was no simple solution. At high rotational speeds, the centrifugal forces tend to move the blades to the plane of rotation. The Rotol 35 required "a total load of about 3 tons" to move the blades [41]. The GE36 prop-fan, discussed later, required nearly 300 kW to rotate the blades at high power outputs.

In its basic application, pitch variation is achieved either by hydraulic systems (with piston actuated by hydraulic pressure, such as Hamilton Standard hydromatic) or electric motors through a set of planetary and bevel gears with motor stop to fix the pitch (Curtiss Electric). Feathering and reversing angles had a range that depends on whether a blade row was single or coupled. The de Havilland single-rotation propeller of the Saunders-Roe SR-45 could reverse to −31 degrees; the CRP could not reverse.

2.5 Engine layout

CRP are powered by single or twin-engines. In the latter case, we define the engines as 'coupled'. According to Ref. [22], coupled engines 'include any of the ways that two engines or parts of engines are put together to create a more powerful engine to jointly drive one propeller or two coaxial propellers'.

Coupled engines are standard propulsion architecture on twin-engined helicopters. For fixed-wing CRP aircraft, known cases include the following: (1) one engine driving fixed-pitch CRP (these are the oldest examples in aviation history); (2) one engine driving variable-pitch constant-speed CRP with blade pitch linked to each other (i.e. Avro Shackleton); (3) twin engines each driving its own fixed-pitch variable-speed propeller (Macchi-Castoldi MC-72); (4) twin-engines driving coaxial variable-pitch constant-speed propellers. In the latter case, there can be two different mechanical solutions: (a) blade pitch control has only one degree of freedom, with the two propellers slaved to each other (Saunders-Roe SR-45); (b) each blade row has an independent pitch control, leading to two degrees of freedom and better power split (Bristol Type 167 Brabazon). An example of twin-engine configurations is displayed in Fig. 5. In case (a), the propeller rpm is the same and the two blade rows are synchronised, and there is one propeller governor (i.e. Convair XFY-1 and Northrop XP-56). In case (b) both pitch and rpm are independent, and the propellers are not necessarily synchronised (Douglas XB-42 and the Fairey *Gannet*). V-drive cases are known to exist at least for one airplane, the Bristol Brabazon. The default architecture of a twin-engine helicopter has a central shaft as in Fig. 4, regardless of whether it is a single or coaxial rotor, with sprag clutches G_1 and G_2 required to disengage one engine if inoperative. There is at least one example of three coupled engines designed to drive a dual propeller: the Allison XT44, with the possibility of disengaging at least one of them [22]. Several derivatives of the Allison turboprop T40 were used with CRP: Douglas A2D, Convair XP5Y-1 and R3Y-1, Hiller X-18 and North American XA2J.

In response to a UK Ministry of Supply requirement for a carrier-based airplane, Fairey Aviation developed a coupled engine in the 1930s, the P. 24, Fig. 6(a). This engine was made of two banks of internal combustion engines (750 kW each) each driving a co-axial propeller. The two propeller shafts made up a coaxial variable-pitch 3×3 CRP developed by Fairey Aviation. When viewed from the front, the fore propeller rotated clockwise powered by the right crankshaft; the aft propeller rotated anti-clockwise powered by the left crankshaft. This engine never entered production[1], although it was tested on the Fairey *Battle* (registration K9370). Its development is described in Ref. [42].

[1]Fairey Aviation produced only two aircraft engines: *Prince* (H.16) and *Monarch* (P.24). All Armstrong-Siddeley piston engines were named after big cats, and turboprop engines were named after snakes. Rolls-Royce piston engines were named after birds of prey, and gas turbines after rivers. Bristol aero engines were named after Greek mythology. Napier mixed-bladed weapons with savanna animals, except for their coupled engines (*Naiad* and *Nomad*).

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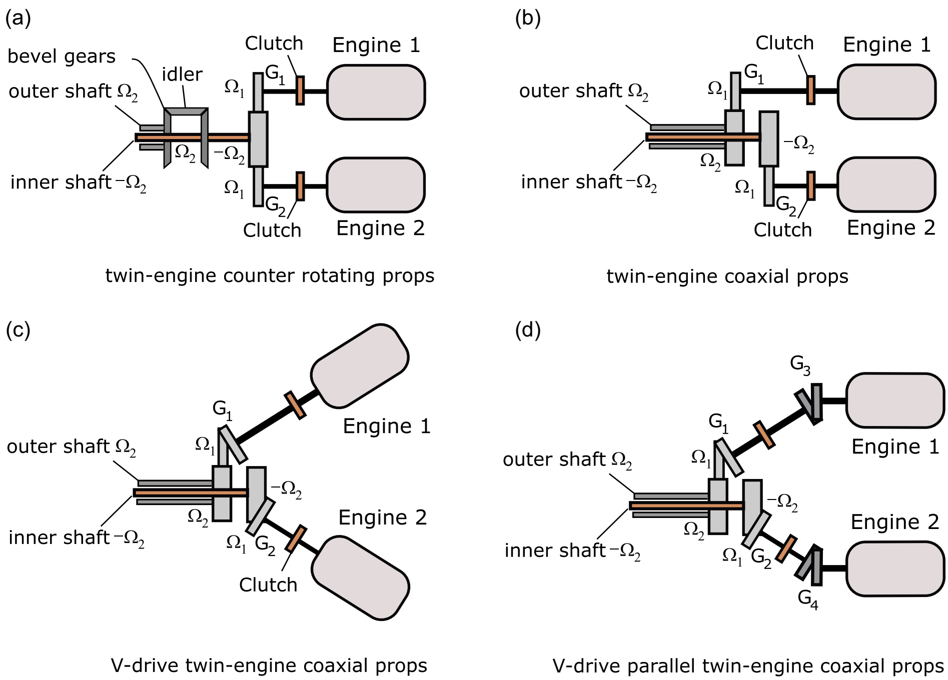

Figure 5. *Examples of twin-engine CRP systems; "G" denotes a gearbox.*

The Napier *Nomad I* (1948–1952), displayed in Fig. 6(c), was a sophisticated engine that had a turbine driving the fore propeller and the diesel engine driving the aft propeller. The two blade rows were not linked together. They could not be powered independently, because the piston engine was required to power the aft propeller, and the engine's exhausts powered the turbine, which was needed to power the fore propeller. A second engine version, the *Nomad II* (1952–1955), mounted single-rotation propellers only [2, 44]. Evolution from the former to the latter is not explained in the available papers, i.e. Ref. [45]. However, Napier recognised its complexity [46] and offered the *Nomad II* for the Avro Shackleton upgrade (four-bladed SRP, Rotol or de Havilland). Diesel fuel and wide-cut kerosene could be used.

A related engine that did not reach production was the Napier *Coupled Naiad*, planned for a Blackburn aircraft. At least one photo with CRP is known (1948), shown in Fig. 6(d). In the discussion of Ref. [42], "the advantage of that engine was that it was a truly contra rotating engine". It was lighter, powerful and had the gearbox aligned with the turbines. Nevertheless, it was cancelled, due to engine development problems. The *Python* engine was coupled to Rotol propellers, not de Havilland as shown in Fig. 6(b).

After the end of the War, Fairey Aviation asked Armstrong-Siddeley to develop an equivalent coupled engine architecture based on the gas turbine. The Armstrong-Siddeley *Double Mamba* (1949–1979) was a coupled engine first designed for the Fairey *Gannet* [42], but then used for the Blackburn B-88 and for the Short S.B.3 *Sturgeon*. Each *Mamba* drove its own propeller, was completely independent from the other one, had separate fuel feed lines, lubrication and control systems. This engine is equivalent to the sketch in Fig. 5(b), and is also shown in Fig. 7(a).

The gas turbine had a 0.0874:1 gear ratio, an 11-stage axial compressor with 5.75:1 compression ratio, and a 3-stage axial turbine. The gearbox and the drive systems weighed 360 kg. Detailed technical data, including power output charts, are reported in Ref. [37]. The starboard engine drove the fore blade row and the port side engine drove the aft blade row. This architecture allowed the propeller to function both as CRP and SRP, with one blade row feathered and braked [14]. Compressed air was used to start

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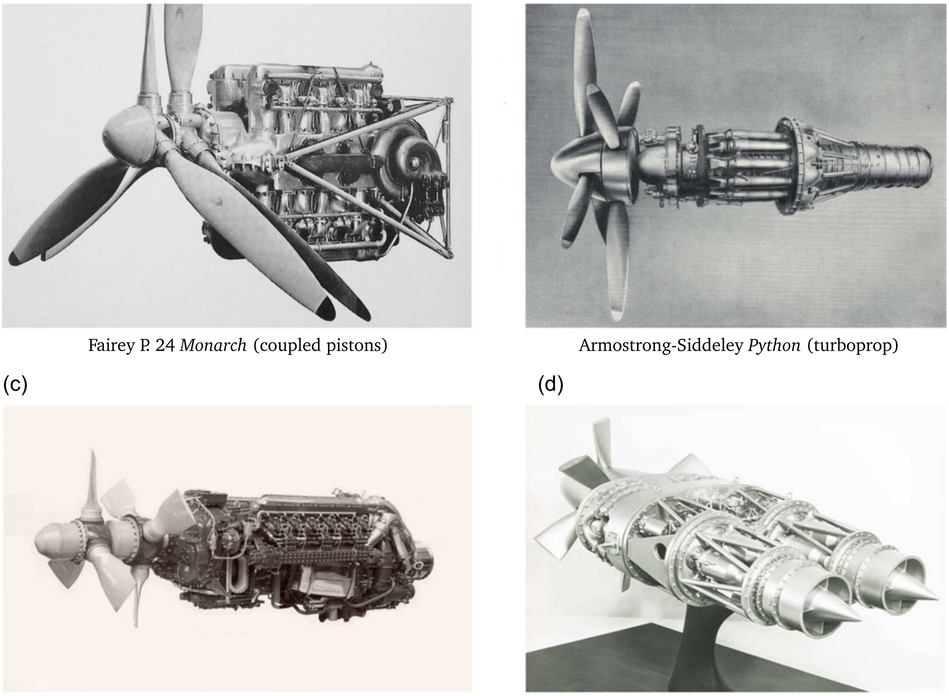


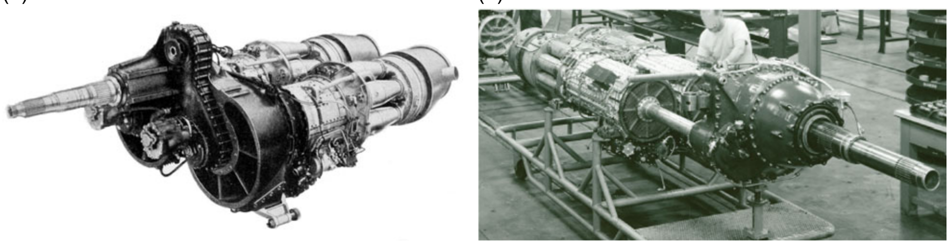
(a) Fairey P. 24 *Monarch* (coupled pistons)

(b) Armostrong-Siddeley *Python* (turboprop)

(c) Napier *Nomad I* (diesel compound)

(d) Napier *Coupled Naiad* (turboprop)

Figure 6. *Four British engines with CRP combinations: Fairey Aviation coupled piston engine P. 24 driving Fairey CRP [[42]; de Havilland hydromatic CRP with Armstrong-Siddeley Python engines [43]; Napier Nomad I with Rotol CRP (Royal Aeronautical Society Archive); Napier Coupled Naiad with unknown CRP (IMechE Photo Archive NAP /4/3/9/5).*



(a) Armstrong-Siddeley Double Mamba

(b) Allison T40

Figure 7. *The British Double-Mamba turboprop (Flight International Archive), and its American competitor, the Allison T40, on the final assembly bench (Allison Archive).*

one engine; engine exhausts fired the second engine. This capability was exploited to limit fuel consumption, particularly in ground manoeuvre and long-range reconnaissance. Unaware of this precedent, the author co-investigated [47] the benefits of using stopped blade rows to reduce fuel consumption and noise emissions at some conditions. Acoustic benefits were demonstrated for blade counts other than $N_b = 3 \times 3$.

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2.6 Blade geometry and construction

Propeller blades from the 1930s were straight, slender and with rounded tips (example, de Havilland propellers [43]). They evolved toward wide-chord square-tipped blades in the 1950s (i.e. Curtiss Electric propeller for the Convair XFY-1), with the improvement in aerodynamic design and stress analysis. A further evolution from recent years produced blades with wide chords, large twist, sweep in both axial and radial directions and finely tuned tip geometries (all modern prop-fans).

In the early days of aviation, blade construction was multilayered wood; materials progressed to full metal (aluminium or steel) and are now almost exclusively advanced composite structures (fibre glass, carbon fibres and hollow composite spars). During 1940–1950, the blades were made of steel (hollow core), Duralumin and Aluminium alloys. There are rare examples of wooden propellers (Shorts S-38).

In the Western world, main manufacturers have been Aeroproducts, Chauviére, Curtiss Electric [5], Rotol (now Dowty), Hamilton-Standard, de Havilland [43], Ratier (or Ratier-Figeac). Fairey Aviation (or Fairey-Reed Airscrews) for some time also produced metal aircraft propellers [48], Fig. 6(a). In the USSR and Russia, the leading manufacturer was Aerosila, and in Japan it was Sumitomo, under license. Curiously, there was not as much interest in Germany, and the leading German propeller company, VDM, did not have a single CRP project [49]. Technical data are available from rare publications by the manufacturers. Each manufacturer has its own identification codes, which may include data such as diameter, number of blades, right/left hand, flange size, spline shaft, minimum and maximum blade angle, materials and more. Weights are given with or without governor and spinner, and they might not be comparable.

2.7 Propulsive efficiency

Early-days concepts focussed exclusively on increasing aircraft speed [25]. If only propeller thrust were involved, increasing net thrust could only be delivered at higher collective pitch, which would load the propeller to a point of diminishing propulsive efficiency. Thus, the idea was to couple a contra-rotating co-axial blade row to take advantage of the swirl of the former propeller wake, and share the load between two rotating disks. An efficiency gain of up to 8% is sometimes reported [50]. This gain is often mis-quoted, which is somewhat concerning. The angular momentum of the wake depends on the torque imparted to the rotor and on the blade count. Lightly loaded propellers do not benefit from a swirl recovery system. Only propellers at the top end of their design load generate enough angular momentum that could, in principle, be recovered [51]. Even then, the contra-vanes pitch must be adjustable.

The technical literature reports graphs [52, 53] of propulsive efficiency of SRP, CRP and turbofan engines versus Mach numbers. Those charts are markedly different among various sources; their origin is unclear.

Normally, the best efficiency is estimated at about 80% ($\pm$2%) for a single-rotation propeller, and 2–6% above these values for a CRP (84–86%), depending on flight Mach number and propeller advance ratio. A notional propeller efficiency plot in terms of advance ratio $J = V/\Omega R$ is displayed in Fig. 8. A theoretical analysis of propeller efficiency [54] for various propeller-wing configurations indicates that contra-rotating prop-fans are better than single rotation propellers because of swirl recovery, although the wing can contribute to this recovery. The propeller-wing integration must be designed together, with the vertical location of the propeller being critical in the overall performance. For a modern design, we have numerical tools that allow us to make parametric analysis and multi-point design.

Alongside propeller efficiency, we need to consider the aero-engine's thermal efficiency. When comparing two propulsion systems, all the intermediate steps must be accounted for. We have the thermal efficiency of the gas turbine η_t (or internal combustion engine), the efficiency of the reduction gearbox and all other gearboxes η_g and the efficiency of the propeller η_p. The result is $\eta = \eta_t \eta_g \eta_p$. A complication arises then the turboprop delivers a non-negligible thrust from the exhaust gases, or when we compare different flight regimes. High propeller efficiency is of little help if the turboprop engine has poor thermal performance, or the gearbox produces excessive power losses, or else there are weight penalties.

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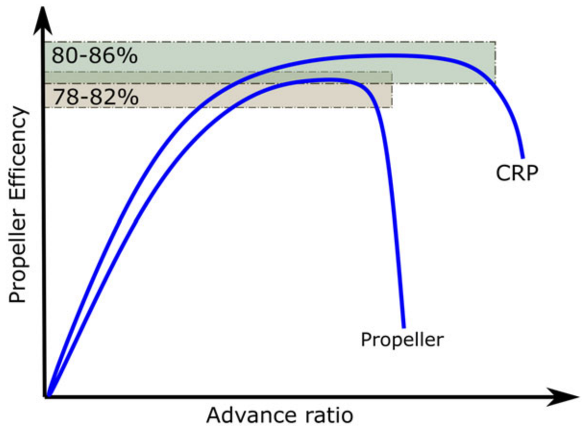

Figure 8. *Notional propulsive efficiency of a conventional propeller and a contra-rotating propeller.*

Propellers are designed to deliver a torque at prescribed flight speeds and altitudes. If the torque available is considerably larger than the design propeller torque, there is a risk of stalling the propeller blades. The design torque can be increased in a number of ways, i.e. by increasing solidity (number of blades and/or blade chord), angular speeds and diameters. Larger angular speeds and diameters inevitably increase tip Mach numbers and thus limit the flight speed. The increase in propeller solidity has the effect of increasing the profile drag, and thus reducing propulsive efficiency. In this instance, the clever idea seemed to be coupling another blade row on a coaxial shaft, and thence produce a contra-rotating propeller with far larger design torque. This solution also required a minimal increase in mass.

Now consider a notional single-rotation propeller with performance chart as shown in Fig. 9(a). This propeller was calculated with the numerical methods explained in Ref. [55]. An operation point at $C_Q = 0.003$ would provide a $C_T = 0.0083$ with a propulsive efficiency $\eta = 0.85$ and a speed of 139 KTAS. Doubling of the available torque to 0.006 would ideally almost double the net thrust. This can be achieved at point B, where the efficiency has now decreased to $\eta = 0.75$, and the flight speed has decreased to 120 KTAS. The corresponding collective pitch has increased. With a fixed-pitch propeller, there is a sharp decrease in propulsive efficiency as soon as the propeller moves from its design point, Fig. 9(b). For example, at $\theta = 30$ degrees, an increase in power is achieved at a loss of 12–14% efficiency (line from C to D): The propeller spins faster and the advance ratio decreases; fixed-pitch propellers are not very efficient.

Propulsive performance is sometimes quoted as specific fuel consumption (SFC), which is incorrect: This refers to the engine only for power delivered at the shaft, without gearing effects. Data are supplied from rated power and fuel flow, which are not always reliable, and in any case suffer from installation, ageing and maintenance problems. In any case, we find SFC for the NK-12MA turboprop at 0.219 kg/kW/h, against 0.228 kg/kW/h for the TP400-D6 turboprop. These are among the best in this class of engines.

3.0 Pioneering contributions (before 1940)

Frederick Lanchester filed a Patent in 1907 (*UK Patent 9413A*) and then proposed a propulsion theory [56]. His ideas were subsequently revised and appeared in 1941 in *Flight Magazine* [57]. Said invention required the torque to be balanced and opposite, something we now understand is not required. There is no record of this contraption having been built.

It is unclear when the first CRP flew successfully, although there is some evidence of one-off projects in the 1920s and 1930s, and earlier historical photographs showing concepts that had no chance of being

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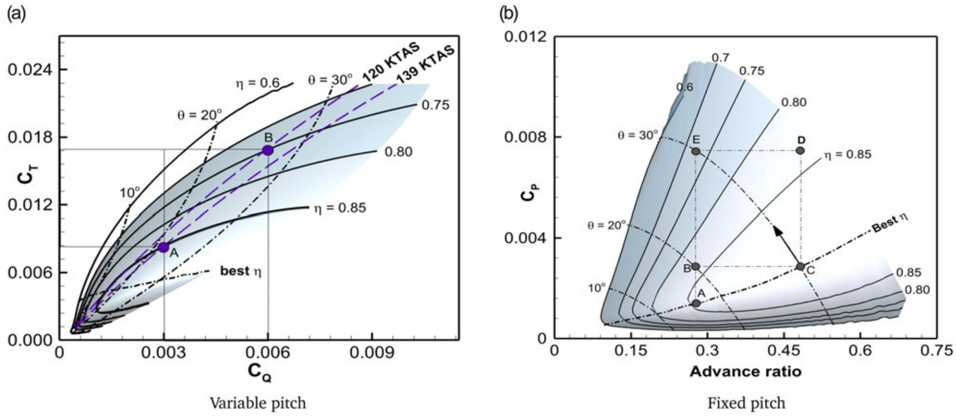

Figure 9. *Notional single-propeller performance, showing the effects of torque, collective pitch, propulsive efficiency and flight speed on the net thrust. Variable and fixed pitch are considered.*

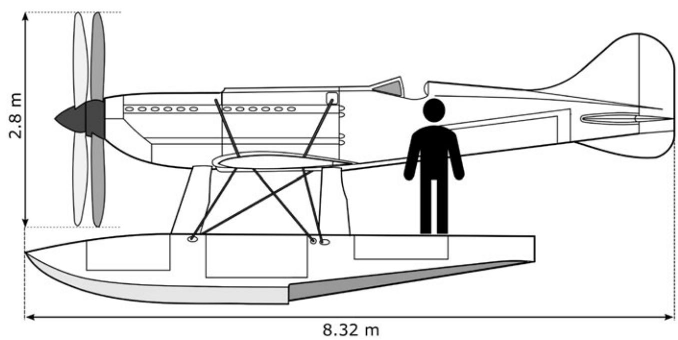

Figure 10. *Sketch of the Macchi-Castoldi MC-72 world-record sea-plane.*

successful, i.e. Ferdinand Feber and Roger Ravaud in France. Documentation from that time is rather limited. For example, a report in *Popular Mechanics* (November 1931) tells of a successful flight of "propellers revolving in opposite direction", with the implication that one propeller was spinning at half the speed of the other one. A Dutch design, the Dekker-Fokker C.1, registered as PH-APL, mounted short turbine-like counter-rotating propellers running at different speeds. Only taxi trials are known (circa 1937), but it is unlikely that the airplane was cleared to fly. A description of this contraption is available in a US Patent by Adriaan Dekker [58].

There are verifiable historical records, such as the 1933 flights of the Italian Macchi-Castoldi MC-72 seaplane for the Schneider Trophy, shown in Fig. 10. The airplane had two-bladed contra-rotating propellers ($N_b = 2 \times 2$; 2.5 m diameter). This airplane had two Fiat AS.6 IC engines mounted in tandem [59, 60], driving two fixed-pitch co-axial propellers. It achieved a speed of 383 KTAS on 23 October 1934, in spite of the drag caused by two large floats[2].

There are prototypes that flew once for a few minutes but then were grounded and the programme cancelled, without a definite assessment of its benefits or drawbacks. One example is the Dutch Koolhoven F.K.55 (1938), with 2 × 2 Ratier metal CRP (variable or fixed pitch, depending on archival sources). It only achieved a 2-minute flight and suffered serious stability issues. The pilot's seat was between the

[2]Fédération Aéronautique Internationale. FAI Record ID = 4497 (ratified); category: speed over a 3 km course.

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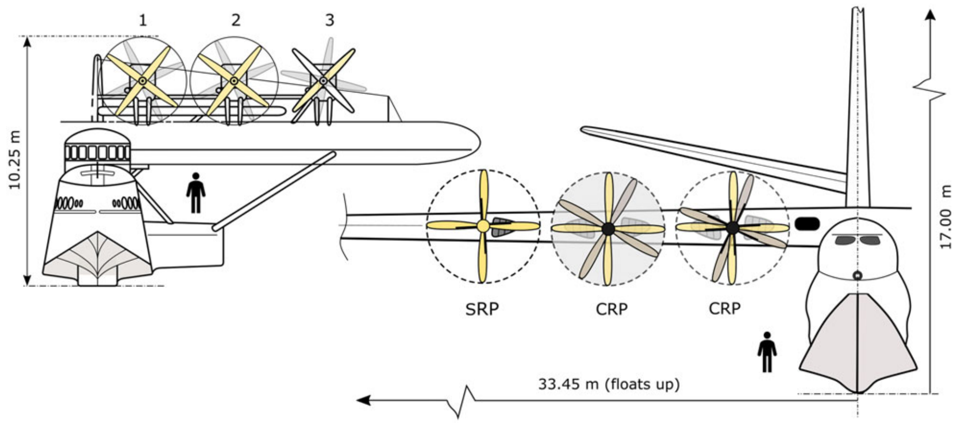

Figure 11. *Sketch of the Dornier Do-X seaplane (1929) and the Saunders-Roe SR-45 Princess (1952).*

propeller gearbox and the engine. This airplane was displayed at the Paris *Salon de l'Aviation* in 1938 and destroyed by German bombing in May 1940.

Examples of tandem configuration include the following: under-the-wing propellers of the Fokker F-32 (1929) and the Farman F-222 (1932–1940); over-the-wing propellers of the Dornier Do-26 seaplane (1938–1940) and Latécoère 300 in France. These were coupled propellers with one tractor prop aligned with a corresponding pusher, shown in Fig. 1(d). In the Farman F-222/2 case, the distance between propellers was ∼2 diameters, with two separate engines on the same nacelle. There are still wake effects, though not in the measure normally found in a closely spaced CRP. Dornier was responsible for similar tandem configurations, with the massive 12-engined Dornier Do-X (1929–1932), with six propellers in tandem (Fig. 11), and the Dornier J Wal (1925–1950), having one tandem four-bladed propeller system.

According to Dornier himself [61], for the Do-X the best solution with the knowledge at the time was to couple two engines on a single nacelle, with each engine powering its own propeller. Driving one propeller with two engines would have required a too large diameter. Other options would have required heavy gears or long shafts. The four-bladed props were manufactured together into a single piece, making them fixed-pitch wooden props with presumably poor aerodynamic aerofoil sections. Propeller characteristics are not mentioned in the official reports, i.e. Ref. [62].

The use of back-to-back propellers does offer some propulsion advantage without the complications of closely spaced rotors. The aft propeller operates in the wake of the fore propeller; this wake is an accelerated swirling flow. The aft propeller takes advantage of higher apparent speed $\sim V + \sqrt{T_1/2\rho A_1}$ and recovers the angular momentum by contra-rotation. One claimed feature of this arrangement was that the failure of one engine would not change the thrust line of the remaining engine.

4.0 A golden era for the contra-rotating props (1940–1950)

A great deal of creativity and risk was taken during the War years. During this time, there was a mix of piston engines and turboprops. Piston engines turned out be obsolete in the rapidly evolving world of aviation, with turboprop engines developing rapidly for high speed flight [63].

The 1930s were dominated by seaplanes with propellers in tandem. They too became obsolete with the development of ground infrastructure that permitted the operation of land-based airplanes. The War years saw an interest in highly powered airplanes, mostly single-propellers capable of operating from/to aircraft carrier: They needed short take-off and landing performance, which was provided by highly loaded CRP. In this instance, the CRP had the benefit of neutralising the torque generated by

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Figure 12. *The Blackburn B-54, WB781 (1949) with Rolls-Royce Griffon engine. It had cranked wings (anhedral/dihedral) that could not fold. Photograph from the Royal Aeronautical Society Archive.*

a conventional propeller, which could have caused the aircraft to roll on its side during a high-power take-off. Just after World War II, a number of military airplanes with CRP appeared and made use of the nascent gas turbine engines, although the transition was slow. These airplanes include the Blackburn B-54, Westland *Wyvern*, Douglas A2D, Martin-Baker MB-5, Shorts S-38 and others, some of which are described as follows.

In the United Kingdom, the Blackburn B-54 (Blackburn Aircraft) was a carrier-borne anti-submarine aircraft making use of pre-war piston engines, the Rolls-Royce *Griffon* 56, shown in Fig. 12. It was originally designed around the Napier Double Naiad turboprop (see Fig. 6(d)). A later variant (registered as WB797) using the Armstrong-Siddeley *Double Mamba* turboprop engine, had 4 × 4 CRP. In this form, the Blackburn Type number was renamed to the Blackburn B-88 [64]. This programme was cancelled when it became clear that the Fairey *Gannet* was a superior aircraft. The same *Double Mamba* engine was installed on the Short S.B.3 with two 3×3 Rotol CRP. The airplane registered WF632 was demonstrated at the 1950 Farnborough Air Show. The looks of this aircraft were certainly unimpressive. Other versions were powered by the Rolls-Royce *Merlin* 140 engines. In any case, a few of these aircraft were operational until at least 1954, both as carrier and land based.

The Westland *Wyvern*[3] W.34 (1946–1958) had 4 × 4 CRP powered by an Armstrong-Siddeley *Python* turboprop engine (version TF.4, later renamed S.4), although the earliest version of the airplane, TF.1 shown in Fig. 13, had piston engines (Rolls-Royce Eagle). Its development was delayed by problems in the propeller mechanical design, a Rotol Type 5. The de Havilland product brochure [43] indicates that they planned to have one of their CRP fitted with the *Python* engine, shown in Fig. 6(b). Its first flight took place in December 1946 and operation was delayed to the 1950s, with the airplane demonstrated at the Farnborough Air Show in 1953; it saw military service in the 1956 Suez Canal crisis. The *Wyvern* was the last Westland fixed-wing aircraft before the company moved into rotorcraft. At least 127 Wyvern were produced in all versions. One version that was to be fitted with the Napier *Nomad I* turbo-compound engine was not completed.

In the same vein, in the US, the Douglas company developed the A2D attack aircraft, of which only flying prototypes and pre-production aircraft were available. The programme was cancelled due to several technical problems, presumably due to the complexity of the propulsion system and the Allison XT40 engine problems. The CRP was a single $N_b = 3 \times 3$ pusher configuration, with fixed-rpm fully feathering blades having sharp-cut tips. The rotor solidity was ∼0.193.

[3]The *Wyvern*, also wivern or wyfern, is a mythical winged dragon.

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Figure 13. *The Westland Wyvern TF.1, first prototype, registered TS371, with Rolls-Royce Eagle engine. Photograph in the public domain.*

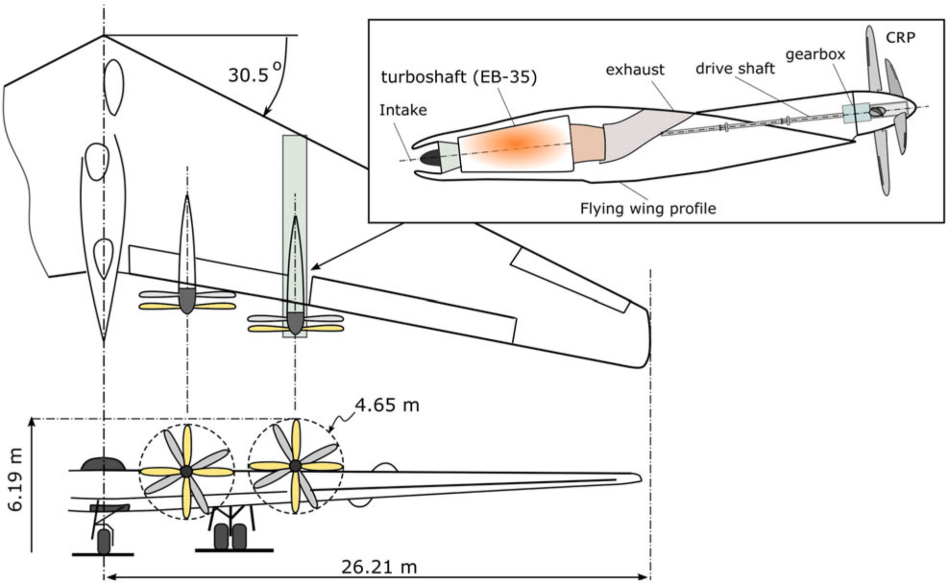

Figure 14. *Sketch of the Northrop XB-35 flying wing and the turboshaft upgrade proposed for the EB-35.*

In the 1940s, Northrop developed the XB-35 flying wing and thus faced a complex integration issue between aft-mounted tractor CRP and the rudderless aircraft. Most of the documentation available is concerned with the flight stability of the flying wing, i.e. Sears [65]. The engines of the initial version were Pratt & Whitney R-4360 Wasp air-cooled radial internal combustion engines and powered the propellers through a very long drive shaft running through the wing (~7 m), as displayed in Fig. 14. Hamilton-Standard developed the contra-rotating tractor propellers (Hamilton Standard type HSP24F60-344). This aircraft evolved into the YB-49 with the replacement of aft-mounted CRP with Allison J35 turbojets. A design with conversion to the Northrop T37 turboprop was named EB-35, but still retained drive shafts across the wing. Even that programme was cancelled, involving industrial relations and government pressure. The programme matured too late (1946), although was intended for war service. The propeller issues were never resolved and involved failures at all levels, from feathering/pitching to vibrations compounded by the long drive shafts.

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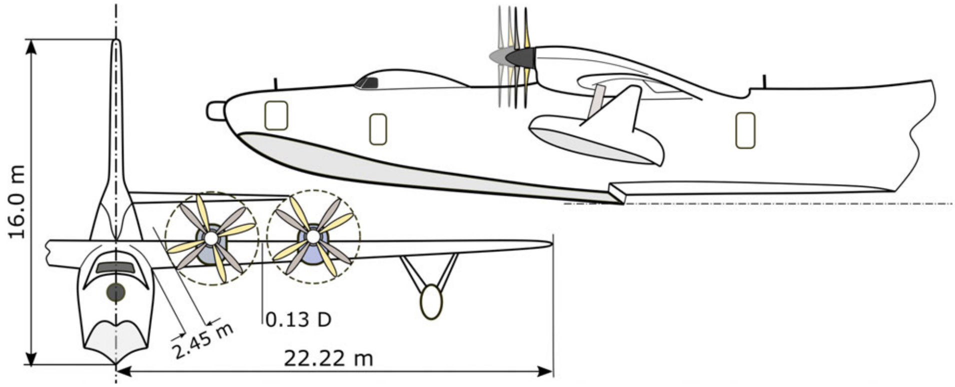

Figure 15. *Sketch of the Convair R3Y-2 Tradewind mounting Aeroproducts 4×4 CRP.*

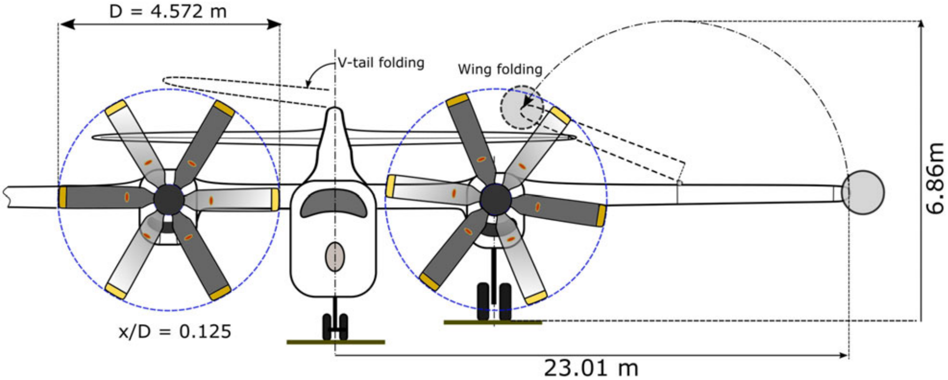

Figure 16. *Sketch of the North American XA2J using Aeroproducts CRP.*

The Convair XP5Y-1/R3Y-1 and -2 seaplanes were novel designs that demonstrated a relative success. The latter one, named *Tradewind*, had a prominent nose radome, shown in Fig. 15. The airplane was a cantilever high-wing flying boat with four Aeroproduct CRP, $N_b = 3 \times 3$, powered by Allison T40-A-10 turboprops, with gear-ratio 0.0630–0.0638 [66, 67], inter-propeller separation equal to 0.13 diameters and propeller water clearance $\sim$2.7 m. The programme was finally cancelled in 1958 because of engine problems and the loss of three aircraft. The R3Y-2 managed to perform unique feats such as in-flight refuelling of four aircraft simultaneously. The XP5Y-1 had Hamilton Standard HS2F117B-24 propellers, with 4.60 m diameter [68].

The Fisher XP-75A was a costly and ill-fated project [69]. This airplane went into pre-production (about 14 built or half built). Of interest was the fact that two types of CRP were tested. Initially, a 3.96 m diameter, narrow, A-blade model was used. However, some of these aircraft flew with another propeller model, a $N_b = 3 \times 3$ blades, with 3.84 m diameter wide-chord H-blade (constant chord, rounded tips).

Several one-off projects were undertaken in the US, including the Republic XP-72 (conventional low-wing tractor with Aeroproducts CRP); the Curtiss P-36 (one CRP flight-tested in 1939, model 75E) and the Curtiss-Wright XF14C (1943–1944) with Curtiss propellers. The Hughes XF-11 (1946), with its Hamilton Standard Superhydromatic CRP was unfortunate, as it crashed on its first flight; a second prototype was fitted with single-rotation propellers. The North American XA2J-1 (1949–1952) was a single prototype powered by Allison XT40 turboprops driving two Aeroproducts CRP with large-chord blades ($c \sim 0.45$m) and gear-ratio 0.064 [70], shown in Fig. 16. Engine problems were contributing factors in the programme curtailment.

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The Northrop XP-56 (1943) was an aft-mounted pusher CRP with $N_b = 3 \times 3$ blades [71], without vertical tail but with a lower safety fin. A first prototype crashed whilst taxiing, and a second one was considered too hazardous to fly, even with design changes; the programme was subsequently stopped. Although the airplane was powered by a P & W R-2800 *Double Wasp* piston engine, an evolutionary concept was to replace it with a turboshaft with improved thermal efficiency coupled to a counter-rotating propellers [72].

The Douglas XTB2D-1 *Sky Pirate* [73] was remarkable: The aft propeller had a larger diameter than the fore propeller (Hamilton Superhydromatic), something we now understand is to be avoided. The Chance-Vought XF4U-4 was a CRP version (Aeroproducts AD7562-X4) of the very successful F4U-4 (H-S Superhydromatic model 624060), so the advantages of the new configuration were unclear. However, the blades of the aft row were instrumented for vibration testing. The Boeing XF8B was again a one-off attempt by Boeing to enter the carrier-borne aircraft business and designed what turned out to be a *one-in-five* single-engine aircraft (1944). It used the same Aeroproducts propeller as the Republic XP-72. Only three airplanes were built; by then the US Navy turned its sight to turbojets [74]. The Curtiss-Wright XP-60 underwent a considerable level of development (-A, -B and -C versions), but ultimately it did not reach production level [75]. Version -C had 3×3 Curtiss Electric contra-propellers named C(46)615S with 3.71 m diameter.

The Douglas XB-42 (1944-1948) had aft-mounted three-bladed contra-rotating puller propellers (3×3, 4.12 m diameter; ∼900 rpm). The aircraft mounted two side-by-side Allison V-1710 piston engines behind the crew's cabin, each driving one of the propellers via two long drive shafts [22] (∼9 m), with a common gearbox to guarantee operation in case of one engine inoperative, as in a Douglas patent [76]; 1.5 m shafts were hinged at each joint by ball-bearing supports to offload deflections. Due to weight balance considerations, the propellers were placed very close to the tail surfaces, but the aerodynamic interference was believed to be small [9]. The aircraft struggled to take-off, due to the low clearance of the vertical fin. Contrary to the claims in said patent, the aircraft experienced severe propeller-induced vibrations, and the programme was cancelled after the second prototype crashed in flight.

There have been a number of other pioneering contributions with a short life. They include Japanese airplanes Kawanishi E15K1 *Shiun* (1941–1944), with $N_b = 2 \times 2$ CRP, reportedly *unreliable*; and the Kawasaki Ki.64 (1943–1944), with $N_b = 3 \times 3$ CRP powered by tandem piston engines, one mounted forward and the other aft of the pilot [77]. This solution required a long shaft, as in cases listed earlier.

There were also French airplanes, of course. Alongside the Arsenal VB-10, there was the Sud Ouest SO 8000, with aft-mounted tractor Chauviére CRP, $N_b = 3 \times 3$, and modified pre-war Junkers Jumo engines [78]. It allegedly failed to take-off in a few instances, but it eventually flew, with poor handling qualities. It was displayed at the Paris *Salon de l'Aviation* in 1949.

The North American P-51XR was a 1980s replica of the original 1940s P-51 *Mustang*; it was powered by a single Rolls-Royce *Griffon* 57 engine, for air shows exhibitions only.

4.1 Flying test beds

A number of semi-obscure flight test beds were developed in this period. Hamilton Superhydromatic 3×3 CRP (Model 624060) appear to have been installed in 1943 on the Douglas B-23 medium bomber [79]. No records were found of this aircraft having CRP in production.

Several versions of the Supermarine Spitfire were tested with CRP; these include[4]: Mk VIII (military registration JK535, with *Merlin* engines), Mk VIII (registration JF321, with *Merlin* engines and de Havilland props), Mk XIV (registration RB144, with *Griffon* engines and de Havilland props) Mk 21 (registration LA219, with *Griffon* 61 engines and Rotol props), Mk 22 (registration PK664, with *Griffon* 61 engines and Rotol props). Two CRP versions of the Supermarine, Mk XIV *Spiteful* (Griffon 69/89) and *Seafang* F.32 (*Griffon* 89 engines) entered limited production in 1944 (about 18 each, depending on archival sources) and served briefly in military operations.

[4]RAF convention was to specify Roman numerals for the Mk I–XVI Spitfire and Arabic numerals for Mk 17 and above.

The Hawker *Fury* Mk 1, registration LA610 (Rotol 35 CRP, 3 × 3, 4.0 m diameter, with Napier *Sabre* engines) was another one-off test; Mk 2 *Sea Fury* reverted to single-rotation propellers [80] (five-bladed Rotol, 3.89 m diameter at 1,200 rpm, $\sigma = 0.153$, with Bristol *Centaurus* engines) and were successful as such.

The Avro Lincoln test bed (registration SX973), powered by the gas-turbine/diesel compound engine Napier *Nomad I*, mounted contra-rotating propellers, but flew only briefly (it was displayed at Farnborough in 1951). The *Nomad I* and the CRP were installed as *an additional propeller* on the fuselage nose, when normally this airplane had four engines/propellers, two on each wing. The propeller had unknown specifications, except that it was a 3 × 3 blades, presumably de Havilland Hydromatic, since these were the normal propeller mounts. A photograph of the time (1948) shows the SX973 *Lincoln* in flight propelled by the *Nomad I* and CRP power-plant, with the four wing-mounted propellers feathered and stopped.

A notable example was the Avro Type 691 Lancastrian V704 (1947), which had inboard CRP (with Avro Shackleton Rolls-Royce *Griffon* 57 engines) and outboard conventional propellers (Rolls-Royce *Merlin*). The mix between CRP and SRP was later found on the Saunders-Roe SR-45 *Princess*. Another Lancastrian test bed was used for testing the Rolls-Royce *Nene* and *Avon* turbojet engines [81].

Most of the aircraft examined were developed in short time due to the pressures of the War. Many practical problems could not be solved. Production problems coupled with changes in operational scenarios (see the Fisher XP-75 case study [82]), meant that some projects became rapidly obsolete.

A summary of key CRP airplanes is provided in the Supplementary Materials (Tables 1 and 2). Engines are internal combustion (IC) or turboprops (TP). The propeller type is CRP pusher (-p), tractor (-t) or tandem. Two values of the propeller diameter are given when fore and aft diameters are known to be different. Where propeller rpm are absent, they are either unknown or variable, with maximum values at take-off and lower values at cruise. The corresponding engines are not indicated, as the same aircraft may have had more than one engine, but notional power ratings are provided. For example, the Westland *Wyvern* started with a Rolls-Royce *Eagle* 22 and was later fitted with an Armstrong-Siddeley *Python* engine.

Propeller manufacturers are listed where known. They are sometimes inferred from high quality photographs, since the manufacturer's logo and blade specifications are printed on each blade (i.e. Fig. 6(a) and (b)). Propeller diameters in bold denote aft diameters larger than fore diameters. Airplane characteristics are indicated by symbols listed in the nomenclature. Power data are approximate, as they may refer to a specific engine version, as reported by archival sources, but not necessarily delivered.

5.0 Western world: 1950 onwards

The Avro Shackleton was a successful long-range transport and maritime patrol airplane, powered by Rolls-Royce *Griffon* 57A engines and de Havilland CRP; it served in at least one war theatre, the Suez Crisis of 1956, and it was finally retired in 1991. Three versions of this airplane are known. The propellers were de Havilland 3 × 3 constant-rpm, fully feathering, with aft blade row slightly shorter than the fore row. Vibrations appeared around 1,500 and 2,200 rpm, and the airframe was subject to fatigue.

The Fairey *Gannet* (1959–1979), also known as Fairey 17, was a carrier-borne aircraft of the UK Royal Navy, shown in Fig. 17, widely documented in the technical literature [14, 42, 83]. Its heavily modified AEW Mk.3 had a large radome on the lower fuselage. Both had four-bladed coaxial contra-rotating propellers with Armstrong-Siddeley *Double Mamba* turboprops and could be started independently.

Blade geometry data (chord, twist, thickness, camber for both fore and aft blades) are provided by Ref. [14]. Differences between fore and aft blade design was noted. The aircraft was noted for its unusually high noise, but it was a unique design of interest to Hamilton-Standard because the aircraft could operate each blade row independently [14]. The blade rows had the same diameter (3.76 m), although the aft row was smaller by 3.8cm because the aft barrel had a larger diameter.

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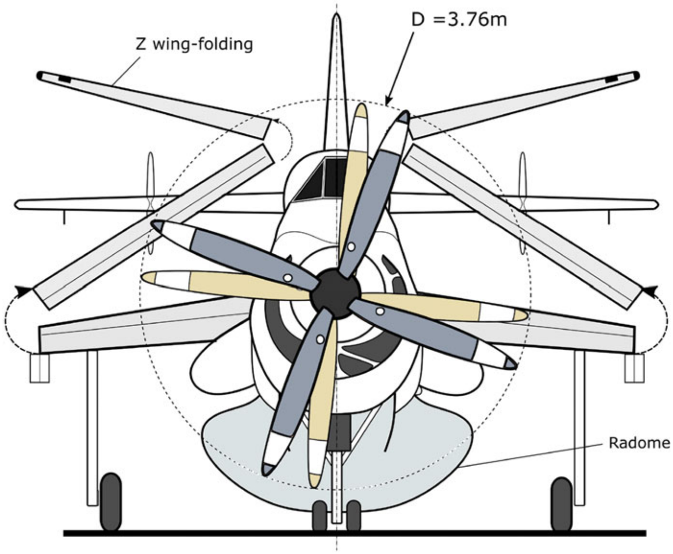

Figure 17. *Sketch of the Fairey Gannet AEW in frontal view. The airplane had a unique Z-folding mechanism for its wings and a large radome fitted under the airframe; it mounted 4×4 Rotol CRP.*

The Bristol Type 167 Brabazon was a massive transport airplane of the 1950s that ultimately had no commercial market; it only operated test flights until it was cancelled by the UK government; the aircraft was later scrapped. In bombastic style, the BBC world service broadcast news in several languages of the airplane taking flight, such was the importance of the event in the British Empire. The four contra-rotating propellers were $N_b = 3\times3$ with a 4.9 m diameter. The complete details of this CRP are given by the Rotol product brochure [84], and include pitch range and weights.

The engineering concepts explored in the design of the power plant are described in great detail in Refs [2, 85]. Eight *Centaurus* engines were placed in couples in a V-drive configuration, shown in Fig. 18, although at least six engine layouts ranging from co-axial to parallel and V-drive were considered. They all rotated in the same direction, and contra-rotation was achieved by means of an umbrella gear (aft prop) and spur gear (fore prop). However, the 1940s Bristol *Centaurus* 18-cylinder air-cooled engines were deemed obsolete for the post-war market, and the project was doomed.

The Saunders-Roe SR-45 *Princess* (1952), said to be inspired by the Dornier Do-X (a 20-year-old project), was a massive flying boat with six sets of propellers, of which the inner four were CRP and the outer units were single rotation propellers (SRP), shown in Fig. 11.

This arrangement was rather bizarre. A general description of the design is given by Brennan [86], who only briefly mentions the propellers. This airplane required ten turboprop engines: eight were to be arranged in couples to power four CRP; two were single-engines each powering the outboard SRP. The inboard engines were eight Bristol *Proteus* 610 turboprops in four pairs. These engines were rated to 3,740 kW when coupled (2× 1,870 kW) plus 7.3 kN of residual thrust [87]. The outboard engines were two Bristol *Proteus* 600, rated at 1,870 kW + 3.65 kN of residual thrust[5]. The specification for the *Princess* was for a 25,000 hp (18,650 kW) power, something that could only be delivered either by large (nonexistent) engines or several of them [88]. Hence the idea of coupling the *Proteus* engines with CRP.

Laboratory tests for this prototype are recorded in Ref. [89], where also off-design issues are reported, such as spray ingestion, propeller stall and damage. Reference [87], which is a report written for the UK

[5]The Bristol *Proteus* turboprops Mk 600 were named -610 for the coupled arrangement and -600 for the single arrangement. The -600 series was considered a failure even by its engineers. The following version -700 was a success; it powered the Bristol Britannia and still appears to hold a valid type certificate with the FAA: E-296, Rev. 3 (May 1959).

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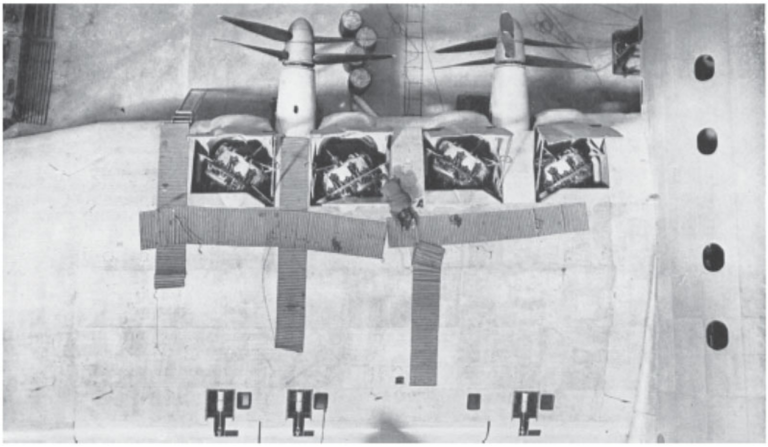

Figure 18. *The Bristol Type 167 Brabazon final engine installation; adapted from Ref. [85].*

Ministry of Supply by the Saunders-Roe company, provides all sorts of specifications, including geometry, aerodynamic data, installed power and propellers. The CRP were manufactured by de Havilland. The gear-ratio was 0.0877:1 for SRP and 0.084:1 for CRP.

Only one aircraft flew (registration G-ALUN, presented at the 1952 Farnborough Air Show), before the programme was cancelled by the UK Ministry of Supply. Many reasons would be invoked, including the fact that corrosion had set in very quickly on stored aircraft. Propaganda films of the time ("Britain's magnificent Transatlantic Flying Boat") mention dimensions, power and exceptional comfort. These news reverberated across the specialised press, including a note in *Popular Mechanics* in September 1949 where it was written that "the plane will have quarters with the comfort and privacy of an ocean liner's cabin".

In truth, the airplane did not perform well on flight testing. Only 45 hours of flights were carried out, with two other ships partially built and scrapped; G-ALUN was broken up in 1967. This project showed a serious error of judgement early on in the conceptual design phase; the reality was unkind to the engineers (Sir Arthur Gouge, a "leading authority in this field") and to the company. Twenty years later, such a ship would have been powered by four turboprops with single rotation propellers, and the passenger arrangements would have been far less luxurious, with the structure being consequently lighter. The age of the seaplane was over by the time the *Princess* was ready to fly. It is a historical coincidence that in 1952 the first de Havilland *Comet*, a true innovation, was commencing commercial service.

An important report in 1954 [26] by Gardiner & Brett (chief engineer and chief aerodynamicist, respectively, at de Havilland Propellers Ltd) states that "it has been found that on the payload-range basis the advantage of the counter-rotating propeller is marginal, even for the longest ranges. In view of this and the extreme mechanical complexity of the counter-rotating hub, the current tendency in design is towards single rotation for all types of propellers".

This view was independently confirmed by Rotol in 1956, when Fairhurst [38], chief engineer, stated that the CRP "has never found favour on civil aircraft, largely on account of its greater expense, complication and more complex service and maintenance problems." Thus, by the mid 1950s both de Havilland and Rotol were aware that the complexity of the CRP design did not warrant further investment, at least in the United Kingdom. The Fairey *Gannet* turned out to be the last UK CRP aircraft. It was a successful design indeed. It was manufactured in large numbers, nearly 350 in various versions for several air forces around the world, and served until at least 1979. It was subsequently used for propeller research by Dowty-Rotol and Hamilton Standard [14].

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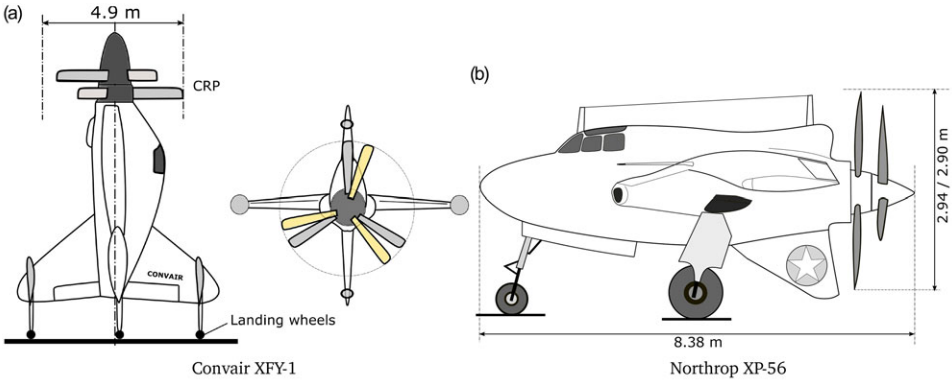

Figure 19. *Sketch of the Convair XFY-1 Pogo experimental tail-sitter and the Northrop XP-56 Black Bullet (different scales).*

In the US, aeronautical research followed a different path. Among the bizarre concepts tried in those years, the Convair XFY-1 *Pogo* (1950–1954) is one that deserves a special mention – a new chapter in the history of aviation, according to Convair. A competing design of the same time, the Lockheed XFV-1 *Salmon*, had the same specifications, same engine and similar Convair CRP. The *Pogo* was a vertical take-off and landing airplane, named *tail-sitter*, shown in Fig. 19. It was placed vertically on the ground (sitting on its tail on four wheeled poles) and it would climb thanks to the powerful dual-rotation Convair propellers with $N_b = 3 \times 3$. It was powered by a single Allison YT40 turboprop, which was made of two T-38 side-by-side turboprops connected by a common gearbox [90, 91]. The power plant was also unique in that Allison recognised that the tip speeds would be transonic in full flight; hence it proposed to have dual-speed gearbox, with one propeller speed for take-off/hover (gear-ratio 20.4) and the other for level flight/dash speed (gear-ratio equal to 11.9). This change in gear-ratio could only be achieved with idle power [22].

The *Pogo* had stability problems, as documented in Ref. [92], a NACA report for the US Navy. This airplane was one of the first to be documented in technical reports following wind tunnel and flight tests of scale models [93]. It achieved at least a couple of remarkable advances: performing flight transition from hover to level flight and back to hover, and flight of a scaled pilotless aircraft. By virtue of the CRP, it did not need another rotor to establish roll and yaw stability in vertical flight. One of the key problems on take-off was the tremendous downwash that would be created by the propellers: It was essentially a helicopter with narrow blades having to propel up to 7,100 kg of weight. In that condition, the downwash would be $\sim$40 m/s, with a mass flow rate through the CRP of $\sim$900 kg/s. By the early 1950s, helicopters had matured to a point where they could provide a variety of aviation services, hence this tail-sitter had no prospect of success. The *Pogo* performed six transition flights before the programme was halted. Reference [90] has impressive close-up photographs of this singular coaxial VTOL.

However, as a followup, an experimental tilt-rotor V/STOL aircraft was tested. This was the Hiller X-18, shown in Fig. 20, precursor of later tilt-rotors. The aircraft was a hybrid airplane/helicopter with tiltable wings. Both the *Pogo* and the *Salmon* required to tilt the complete aircraft. However, it became clear that if propellers were to be used to produce lift and thrust, it would be more rational to maintain aircraft attitude and tilt the rotors [94]: The tilt-wing was born.

The propellers were Curtiss-Electric CRP operating alongside jet vectored thrust. The wing pivoted around 35% chord. This was the first successful attempt at tilt-wing concepts, with engines from surplus *Pogo* and *Salmon* projects [95, 96]. It was powered two Allison YT-40 turboprops and a Westinghouse J34 turbojet that delivered up to 15 kN thrust for pitch control. A number of problems were found, of which we mention the propellers position with respect to the pitch axis, a gyroscopic effect created by wake bending (which increased the power required to tilt the wing), strong ground effects [97] and

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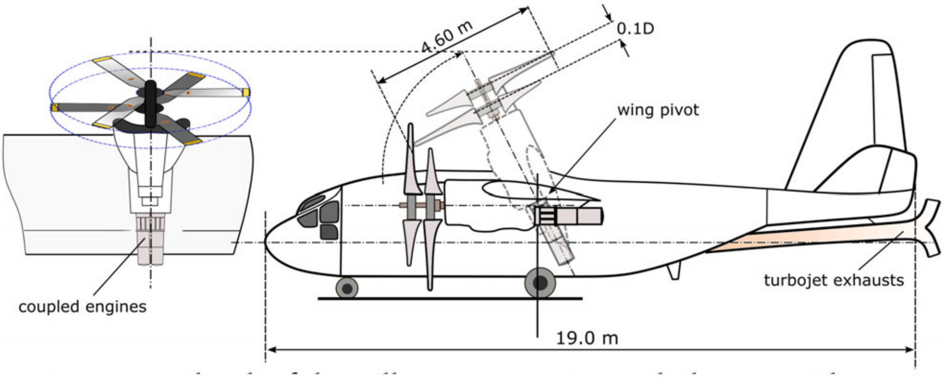

Figure 20. *Sketch of the Hiller X-18 experimental tilt-rotor with CRP.*

landing difficulties. It would not be allowed to fly on modern regulations, even experimental type certificates, because it lacked a cross-shaft connection between the engines. Failure on one engine would have been catastrophic.

6.0 Soviet union, 1960s and 1970s

The CRP was particularly successful from the 1960s onwards in the Soviet Union, Russia and Ukraine. The Kuznetzov NK-12 became the engine of choice for quite a variety of airplanes, having been developed over a long time. It is reported that the conception of this engine goes back to the early years after World War II, with Austrian engineer Ferdinand Brandner (1903–1986) playing a major role in the project. The engine was named "NK", after Nikolay Kuznetzov, chief designer when the product became a reality, although the original name was "TV" and was the result of efforts from post-war German engineers.

First flights with this engine took place in 1954 and 1955. The engine has a 14-stage axial compressor and a 5-stage turbine on a single shaft. The compressors have variable inlet guide vanes to maintain good efficiency across stages and power outputs, and is able to deliver a peak compression ratio ∼ 13:1. This engine series deliver over 11,000 kW of shaft power in its various versions. The NK-12MV is rated to 15,000 hp, or 11,863 kW. Operating at 730 rpm, the corresponding torque would be ∼155 kN m.

The *Tupolev Design Bureau* produced the long-range bomber Tu-95M (1956-present), the Tu-114, the Tu-116, the early-warning aircraft Tu-126 and the Tu-142, all powered by the NK-12 turboprop.

The Tupolev Tu-91 (1955) was a prototype low-wing monoplane, initially intended as a carrier-based bomber aircraft. A single frontal 3 × 3 CRP was powered by a centrally mounted Kuznetzov TV-2 turboprop engine via a long drive shaft; the pilots' seat was between the propeller and the engine (as the Koolhoven F.K.55); the exhausts were behind the wing's trailing edge.

In the case of the Tu-95, the CRP was $N_b = 4 \times 4$ (fore and aft, respectively, at 750 rpm), fully reversible props with a 5.6 m diameter, called AB-60. These blades have maximum chord of 0.475 m, a relative thickness of 4.17% and have been designed by TSaGI, the Central Aerodynamics Institute. The weight of propeller and parts, spinners, electrical de-icing system is estimated at ∼1,190 kg. The blades are made of aluminium alloy with a central H-spar. The distance between rotor disks is 0.650 m, equivalent to 0.108 diameters. This airplane is still flying in large numbers for reconnaissance and other missions, shown in Fig. 21.

The Tupolev Tu-114 used similar power plants and CRP [98]: Kuznetzov NK-12MV and Aerosila AV-60N propellers, shown in Fig. 22. The 5.6 m blades required very long landing gear struts, making the aircraft unusually tall. The nose landing gear strut was over 3 m long. This was a very successful aircraft that operated both USSR domestic and intercontinental flights (including flights to Amsterdam,

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Figure 21. *Three Tupolev Tu-95 flying over Moscow in close formation (May 2020).*

Figure 22. *Propellers of the Tupolev Tu-114 (CCCP 76486). Still frame of a video clip at Amsterdam Schipol airport on 1 June 1964. Credit: Nederlands Instituut voor Beeld en Geluid.*

Tokyo, Montreal) from 1962 until about 1976. There are reports of intense cabin noise at positions near the plane of rotation of the propellers, but no acoustic data are publicly available. The Tu-114 held several aviation records, i.e. FAI record No. 8880 (speed over a closed circuit of 1,000 km with 25,000 kg of payload).

The *Antonov Design Bureau* produced the An-22 (1965 onwards), likewise powered by the NK-12MA turboprops and the same type of propeller blades. The rotors are not synchronised, and the propellers ground clearance is higher than the average ground operators. Figure 23 shows a photograph of the aircraft taxiing on the unpaved runway of Gao airport (ICAO: GAGO), in Mali (2016). Enormous dust ingestion and dust clouds were recorded, but the aircraft could nevertheless deliver large cargo.

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Figure 23. *Antonov An-22A Antei (Registration UR 09307) landing on dust at Gao airfield, Mali, in December 2016. Still frame of a video clip by the Antonov Airlines.*

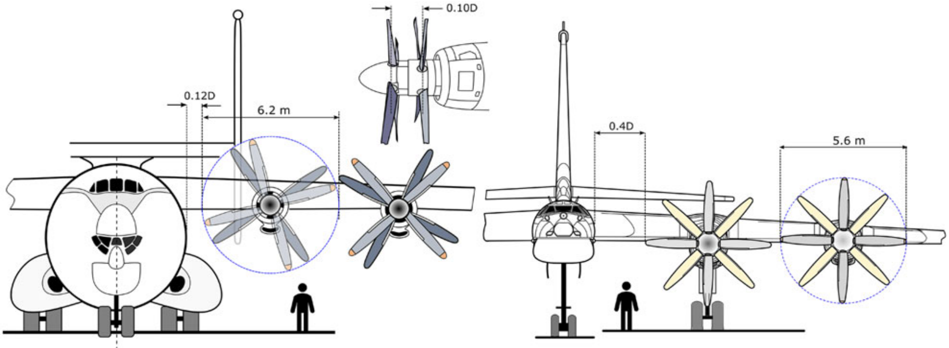

Figure 24. *Sketch of the Antonov An-22A and Tupolev Tu-95 side by side.*

The CRP architecture was the same as the contemporary Tupolevs, but with a modified propeller AB-90 and a larger 6.2 m diameter, according to Ref. [99]. A sketch of the An-22 is shown in Fig. 24 alongside the Tu-95, for comparison. General design aspects of some of these aircraft are described in Ref. [100], with more detailed documentation in a Russian manual from 1971 [101].

Following the political crisis in the Soviet Union in the early 1990s, airplanes that were first registered as CCCP- were split between the Russian Federation and Ukraine, and registered as RA- and UR-. The first production airplane was CCCP-56391 (November 1965). The last remaining airplane in service with the Antonov Airlines, registered as UR-09307, Fig. 23, was destroyed in March 2022 during the Russian invasion of Ukraine. A few airworthy An-22 remain in service within the Russian Federation.

One argument put forward by the design teams is that the availability of large shaft power from the NK-12 turboprop would normally require an increase in propeller diameter. The NK-12 turboshaft appeared to have been developed somewhat independently of the propeller itself. It is likely that the airplanes that used this engine required CRP because this was judged the most reasonable solution to deliver the torque available at the required speed.

The Antonov Bureau also designed the short take-off An-70 (planned in 1984, operational in 1994), powered by four Ivchenko-Progress D-27 three-spool turboprops. This aircraft was intended to modernise the An-12, a four-engined single-propellers aircraft. The Antonov An-70 is the only one, among the examples shown, that has a different blade count between propellers: $N_b = 8 \times 6$ blades, fore/aft, respectively, at 1,200 rpm, with a 4.5 m diameter, axial separation $x/D \simeq 0.35$. This CRP is known as SV-27, Figs 4 and 25. The rotor solidity is considerably larger than the previous examples. The propellers have a wide chord with a maximum value of ~ 0.60 m, tapering toward the tips. This leads to an estimated solidity $\sigma \simeq 0.170$ and 0.127 for the fore and aft propellers, respectively.

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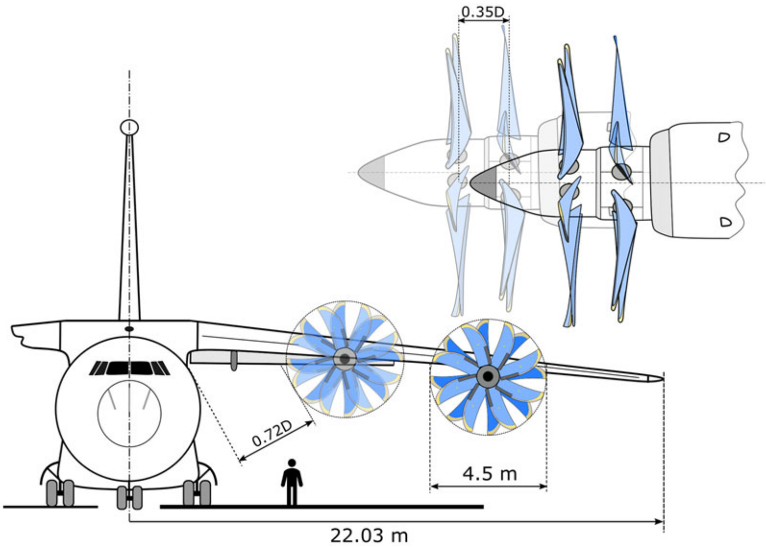

Figure 25. *Sketch of the Antonov An-70 and its SV-27 CRP.*

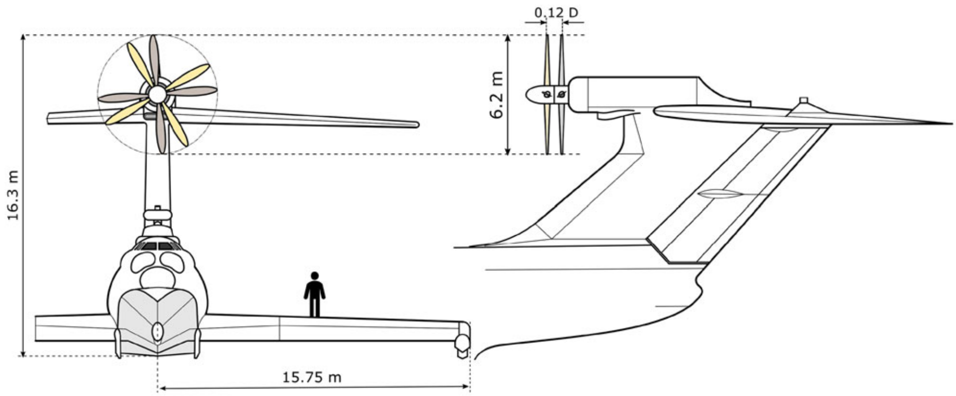

Figure 26. *Sketch of the A-90 Orlyonok central CRP (Aerosila AV-90).*

Both power-plant and CRP configuration were used again in the aft-mounted engine of the A-90 Orlyonok, an airplane essentially designed for ground-effect open-water operations. This is sketched in Fig. 26. The airplane is no longer operating. Presumably, flying close to the water caused non trivial risks. A single CRP with $N_b = 4 \times 4$ and a 6.2 m diameter was mounted atop the central vertical fin; it was powered by an NK-12MK turboprop, alongside two NK-8-4K jet engines mounted lower, near the bow of the ship. Not much information is available on these propellers, and it is not possible to assess propulsive efficiency and noise.

The Ilyushin Il-76LL (1987) was a test bed with a single Lotarev (Ivchenko Progress ZMKB) D-236 engine replacing the inboard right turbofan engine [102]. This installation is shown in Fig. 27. CRP characteristics included the following: 8 × 6 Aerosila blades, 4.20 m diameter, torque split estimated at 41%/59%, rpm variable from 960 (cruise) to 1,100 (take-off/climb-out) and a design 73.4 kN net thrust. This propulsion system was designed to fly at 11,000 m (36,000 feet) at $M = 0.7$. The blades were made of glass carbon-fibre and carbon composites with a metal spar.

Likewise, the Yakovlev Yak-42E-LL was a test bed [103, 104] with aft-mounted 8 × 6 CRP, with the same engine type, D-236. This prop-fan was mounted on the right side, whilst the left side retained

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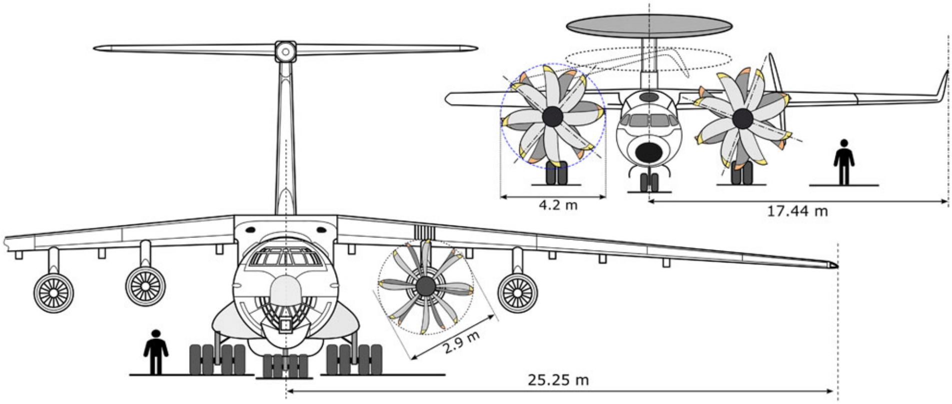

Figure 27. *Sketch of the Ilyushin Il-76LL test bed (bottom) with a single prop-fan and Yakovlev Yak-44E AEW with two wing-mounted prop-fans (top).*

the D-36 turbofan engine in test flights. A further version, the Yak-44E, was an early warning airborne aircraft, of which only one prototype was built. For this version, both engines were prop-fans, with $N_b = 8 \times 6$ CRP.

7.0 The 1980s and the fuel crisis

For about 25 years research and development of CRP was almost halted in the western world; the period between 1960 and 1985 saw little activity. In the 1980s, research was scaled up to respond to the high price of fuel at that time. The mechanical complexity of the propellers did not deter the industry from seeking economical solutions at a time of crisis [19, 105].

Modern CRP arising from the mid 1980s onwards are based exclusively on gas turbine engines and are commonly known as prop-fans. The main architectures are geared CRP (both pusher and puller/tractor) and direct-drive CRP. A direct-drive CRP (also known as direct-drive contra-rotating open rotor) only exists in the tractor configuration. This is because the CRP are coupled with the power turbine. A summary of propulsion architectures is displayed in Fig. 28, where there is a mix of geared and ungeared (direct-drive) counter-rotating prop-fans. Configuration (b) is representative of the P&W/Allison 578-DX with the exhaust lobes interfering with the blades. Configuration (d) represents a prototype such as the Kuznetzov NK-110, and configuration (e) is similar to the Kuznetzov NK-108.

A summary of data is provided in the supplementary materials. Thanks to the increase in open-source documentation, we have data such as torque split, pitch settings, activity factors, tip Mach numbers and a variety of geometric and aerodynamic data. The propulsion efficiency benefits have been demonstrated in a number of programmes [106–108], but they are mostly limited to test beds. These benefits are up to 20% improvement in fuel burn over comparable turbofans. The GE36, the P&W Allison 578-DX, the Ivchenko-Progress ZMKB D-236 and D-27, and the Safran Open Rotor are modern CRP prop-fans.

The P&W/Allison 578-DX prop-fan was tested on a McDonnell-Douglas MD-80 [109]. The Allison turboprop was a modified version of a helicopter turboshaft engine (Allison XT701) and used electronic engine controls from P&W. The programme required replacement of one of the JT8D turbofan engines with the 578-DX. CRP characteristics included the following: $N_b = 6 \times 6$ blades rotating at 1,235 rpm, with 3.535 m diameter, axial separation $x/D = 0.186$, differential planetary gearbox and torque split estimated at ∼55%/45%, at flight $M = 0.72$ and altitude of 35,000 feet.

Several problems were encountered both in ground and flight testing, of which we mention a few. To begin with, the exhausts (nine circumferential tubes) were upstream the two rotors; thus, hot gas impingement on the fast-rotating blades was inevitable. This gas impact generated heat loads on the

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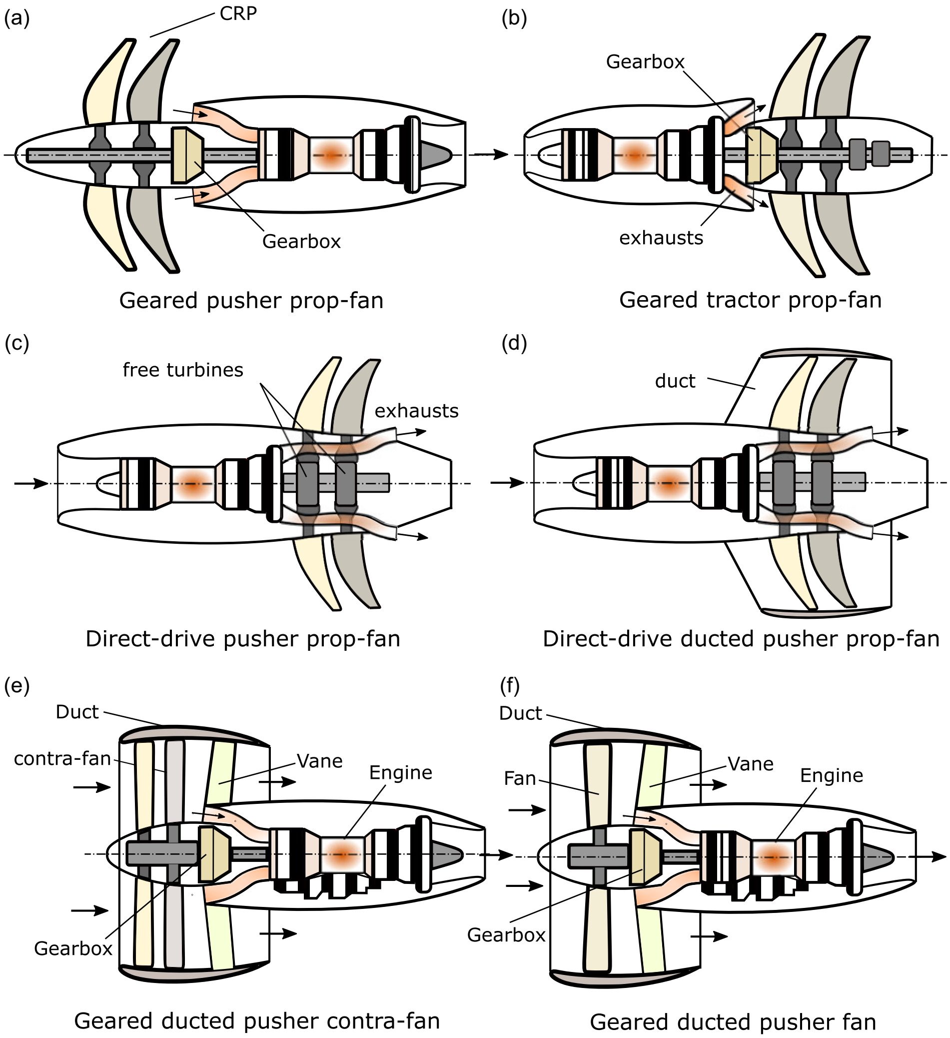

Figure 28. *Selection of advanced prop-fan configurations.*

blades and an additional buzzing noise. Furthermore, this demonstrator could not meet One Engine Inoperative (OEI) criteria at take-off if the JT8D-209 engine had to be shut down.

The General Electric GE36 [110] concept was called UDF (Unducted Fan Engine) and was extensively ground-tested in 1985–1986. It demonstrated a fuel consumption rate 20% better than competing turbofans. The engine was then flight-tested on a modified Boeing B727-100 in 1986–1987 [105, 106] jointly by the Boeing Company and General Electric. The baseline Boeing B727 was an aft-mounted tri-jet configuration. For these tests, the GE36 prop-fan engine was mounted on a starboard pylon, whilst the original JT8D engines remained in place at the port-side and the central position. CRP characteristics included the following: 8×8 blades, 3.557 m diameter, collective pitch range of 86 degrees, 33/29 degree sweep angles (fore/aft rotors), axial separation $x/D = 0.172$, rotating at 1,390 rpm, with aft blade row operating at $M > 1$ at flight $M = 0.72$ and altitude of 35,000 feet. The GE36 engine was 1.25 m shorter than the P&W Allison 578-DX, but 1,140 kg heavier.

NASA's Advanced Turboprop Programme (1976–1988) deserves a special mention [50], as it provided tests and data on a variety of single-rotation and contra-rotation propellers (Ref. [50] also includes

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an extensive bibliography). In particular, a single-rotation system named SR-7L consisted of eight highly swept blades, 2.74 m rotor diameter, 41 degree sweep, rotating at 1,700 rpm and generating 40 kN of thrust. It was mounted on the left side of a Gulfstream G-II [111, 112] (1986–1988). In fact, considerable work was done to assess single- versus contra-rotation propellers [113]. En-route noise measurements at a variety of altitudes have been reported in Ref. [114], and indicate noise peaks of 70 dB at $M = 0.7$ and altitude of 30,000 feet. This is relatively high in comparison with modern airplanes.

Russian research also moved toward prop-fan and ducted fan concepts. From the late 1980s, Kuznetzov developed the NK-110 [52]. This engine used a three-shaft architecture with a pusher prop-fan consisting of two co-axial, 4×4 blades, 4.7 m in diameter, with variable pitch. A three-stage turbine powered the prop-fan through a planetary differential reduction gearbox. The NK-108 variant had tractor propellers. Only papers and drawings are known to exist.

A noteworthy aircraft is the Dornier *Seastar* CD2 [115] seaplane (1984–2020), which has two propellers in tandem powered by two P & W PT6A turboprop engines ($N_b = 4 \times 4$, with 2.40/2.35 m diameter).

8.0 Recent developments

A large number of prototypes have been tested in the wind tunnel as part of research projects to provide both aerodynamics and acoustics data, i.e. NASA's F7/A7 model in Ref. [116] (11×9 blades, with 0.622/0.607 m fore/aft diameters), the F7/A3 model in Ref. [117] (same number of blades, smaller aft rotor), and a host of other CRP configurations. NASA's nomenclature for these systems was to associate a fore blade design number, for example fore F#7, with an aft blade design, i.e. A#7.

One important difference between the designs F7/A7 and F7/A3 is that the latter one has the aft blade row clipped. Other prototypes have been tested in the wind tunnel only for specific reasons, such as blade flutter under high loads, i.e. the F21/A21 CRP [118], $N_b = 13 \times 10$ blades, 0.62 m diameter at tip Mach numbers $M = 0.715$. Several other F#/A# combinations are documented by Ref. [119].

Other configurations tested include the F31/A31, F39/A31, which achieved mixed results. The latter, in particular, had a fore rotor with forward swept blades; it demonstrated poor aero-elastic performance and interaction tone noise levels 8 dB above the F31/A31 reference case [120]; this was not a good idea. A compendium of this research is given in Ref. [105].

More recent designs have been proposed by the CFM consortium and Airbus, such as the A1-PX7 laboratory model [121] (11×9 blades) with a 10% aft-rotor clipping, $x/D = 0.22$, hub-to-tip diameter ratio equal to 0.35, and design thrust of 10 kN. The data published for this case are vague, as they lack numerical values for context and comparison.

Safran in France has been developing CRP for a number of years, both direct-drive and geared engines. Various levels of multi-disciplinary design and optimisation [122] have produced extremely complex blade geometries that are swept radially and axially; the new blades look like flags in the wind shown in Fig. 4. Aft-blade clipping is 15% in the latest available version, HERA5. The engine is a derivative of a turbofan engine (Snecma M88) converted into a turboshaft. Unlike the 578-DX prop-fan, the exhaust gas duct is inside the nacelle. Exit is past the aft propeller. The whole propulsion system is mounted on a pylon inclined about 35 degrees from the horizontal plane. This open rotor has been seen spinning for ground testing, but at the present time there is no evidence that it is qualified to fly.

A Rolls-Royce project (company specification RB3011) was a conceptual design having both pusher and tractor configurations (8×7 blades). After wind tunnel aerodynamic and acoustic testing in two different facilities (2008–2010), the project was seemingly left behind (i.e. Rig 145, 1:6 wind tunnel model, build 1 and 2, with varying number of blades, the latter with 11×9 blades). Acoustic data and installation effects were published in a number of papers.

The contra-vanes concept has been revised in recent research (2015 onwards). This research includes a Safran open rotor (single pusher propeller with variable-pitch swirl recovery vanes, 11×10 blades), and others, i.e. Ref. [123] and related papers. In the latter case, a six-bladed rotor with four contra vanes

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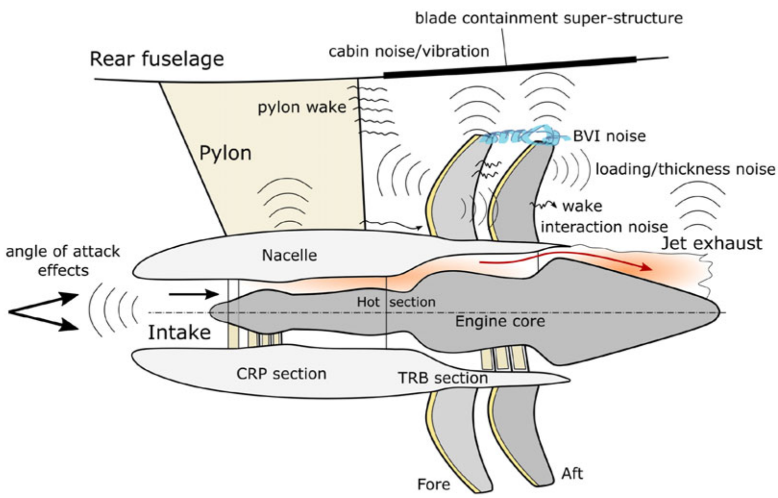

Figure 29. *Sources of noise and vibration on a modern aft-mounted prop-fan.*

has shown marginal propulsive gains alongside poor aero-acoustic response in laboratory conditions: high tonal components at several multiples of the blade passing frequency have been demonstrated.

9.0 Noise issues

Noise remains one of the unsolved problems of the CRP. The literature on this subject is too vast to be qualified in this context, and it mostly refers to laboratory conditions. Research in the 1950s was modest. After recognising the role of the helical tip Mach numbers, the propeller-fuselage distance, propeller synchro-phasing (mostly for cabin noise annoyance), Ref. [26] acknowledged that "there is little that can be done in the design of the propeller itself to minimise the noise problem."

On the practical side, there is evidence that the Tupolev Tu-95 is extremely noisy, both outside and inside the cabin, though no measurements prove the actual noise levels; it has been heard from underwater submarines. As reported in Ref. [124], the Tu-95 was "one of the loudest aircraft ever built", with pilots reporting serious ear discomfort during flight. Yet, it is still flying, as shown in Fig. 21. The Tu-114 was presumably the same, but there are no published data to assess either cabin or external noise. There is evidence that cabin noise was highest on the plane of the rotor, which we would expect. The fundamental blade passing frequency of these propellers is less than 50Hz. Hence noise can be detected by instruments several miles away, with the airplane out of sight.

High noise levels were reported for aircraft such as the Blackburn B-54; again, no measurements are available. Retrieval of air shows bulletins indicates that noise was not a concern back in the 1950s. For example, at the Farnborough Air Show of 1950 both the Bristol Type 167 Brabazon and the Westland *Wyvern* TF.2 were on display. In the former case, there are comments [125] on the mass balance of the control surfaces, "an offence both against aesthetic and aerodynamic principles" – nothing about noise. The first noise regulations only came into force in 1972 (ICAO Chapter 2). Research has much advanced since then, and the current focus is on prop-fans and open rotors. A sketch of noise propagation and vibration sources is displayed in Fig. 29. Interaction noise between blade rows and between CRP and airframe elements (pylon, fuselage) are recognised as critical contributors to the overall noise and vibration response.

The first acoustic measurements known to this author are those carried out on the Avro Shackleton in the early 1980s [126]. Flyover acoustic data were taken, but the actual values are not produced in the

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research. Interestingly, though, noise from synchronised engines is considerably lower than unsynchronised engines, possibly 10–15 dB, depending on the emission angle. Propeller phase synchronisation has since been an important area of research, i.e. Ref. [127].

Acoustic measurements were taken by Parzich & Shattuck (1986) on the Fairey *Gannet* [83] at full power and 50% power. The aircraft was modified for acoustic testing, and included microphones in the plane of the rear rotor. Data are published on acoustic directivity, front and aft propeller noise split, harmonic content and interaction noise. Flyover noise data indicated showed 98 EPNdB with a microphone placed 1.2 m from the ground. Flight and measurements were carried out following FAR Part 36 regulations. The CRP noise was estimated ∼1.5 EPNdB higher than a single propeller with the same output power. A comparison between these flight data and acoustic predictions was shown by Hanson [128], where a comparison for the first four harmonics is shown, and Parry [129] (without SPL levels).

In a report by the Boeing Company [130] on the UDF engine it was demonstrated how installation effects can add several dB of tonal noise. This result was confirmed by Airbus and others [131] on a scaled prop-fan wind tunnel model; at least 5 dB were added by pylon interaction. Russian research on their advanced prop-fans [132] reported acoustic loads of 140–150 dB in the aft-empennage, requiring structural upgrades.

It has been now established beyond doubt that clipping the aft blade row leads to a noise reduction [133, 134]. From this point of view, configurations with larger aft diameter are well past the state-of-the-art. Likewise, sharp-cut leading edges must be avoided.

The earliest known formulation of CRP noise is attributed to Hubbard in 1948 [135]. Acoustics became more focussed in the middle of the 1980s, with a flurry of important research released from that time onwards [128, 129]. This strand of research is now dominating the scientific debate on CRP.

10.0 Critical discussion

The 1950s were characterised by the transition from piston engines to the gas turbine. Even when the turbines proved unreliable (i.e. various Allison T40 versions), progress was relentless and the combustion engine lost its central role. Projects that started with piston engines were converted to turboprops (Northrop XB-35, Blackburn B-54, Douglas XB-42, Westland *Wyvern*) or cancelled all together (Bristol Brabazon, Saunders-Roe SR-45). Projects that started with CRP (Northrop XB-35, Hughes XF-11), were converted to single-rotation propellers. This process saw the demise of incredible feats of engineering, such as the Napier *Nomad* turbo-compound, which claimed unparalleled SFC [45].

Some failures are attributed to scarcity of time, in spite of laudable resources and creativity. The engineering tools were also limited, and the *I-know-best* approach prevailed – until it was proved wrong.

A critical flaw in the approach evidenced by both patent and technical literature is that the solution of an individual issue would open the route to a successful development of the CRP. It is entirely possible that a CRP with an advanced turboshaft has a lower SFC relative to a conventional power plant (all other key operational parameters being the same), but the overall direct operating costs are higher. Fuel is not necessarily the highest cost item; quoting fuel prices as a driver for this propulsion system is misleading: excessive maintenance burden may erode any gains from fuel burn savings. The higher acquisition cost of the CRP/prop-fan may well overshadow the cost of a conventional gas turbine engine.

The differences in operating costs, relative to a conventional aircraft, can be estimated from the changes in power-plant operating costs, including fuel burn. Reference [136] has a propulsion reliability analysis to establish the likely operating costs and risks for and advanced prop-fan. These estimates are incredibly difficult to carry out, and can only be verified after considerable flight testing. Reference [136] also considers the replacement of twin engines under the wing, and the analysis seems to point to nearly the same operating empty weight. After nearly 40 years, this configuration has not materialised.

Today we use conceptual engineering design, an approach based on the rational assessment of top level requirements. At the detailed level, with the multi-disciplinary computational methods available today, it is possible to design an advanced single-rotation propeller that matches or surpasses a CRP on

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several metrics, including propulsive efficiency, acoustic emissions, overall weight and costs. The latest developments focus on incremental improvement of performance across multiple constraints: acoustics, structural dynamics, aero-thermo propulsion, system integration, operating costs. Some gains have been demonstrated over the baseline of the 1980s designs [137], when such advanced methods did not exist.

The author's view is that a feasible solution would be a prop-fan that entirely replaces a turbofan on an existing airframe, with minimal changes to the airframe itself. This solution would only be possible for aft-mounted engines (airplanes as the MD-80, which require changes in the supporting nacelles only, unless there are sensible changes in CG position) or as replacement of wing-mounted turboprops (i.e. Bombardier Q400). In fact, parametric analysis of engine placement on the MD-80 indicated that the aft-mounted prop-fans yield the most benefit, including noise. From a safety point of view, prop-fans mounted on aft pylons provide some containment to rotor failure (*blade out*), because a blade impact with the fuselage would not cause cabin depressurisation [105]. For prop-fans mounted under the wings, there would be a need to strengthen the fuselage to contain the blades, alongside additional noise shielding. The limited ground clearance would in any case prevent this solution. Even this is an optimistic assessment, because recent research has indicated that prop-fan and airframe integration is critical to the viability of the CRP. Retrofitting a prop-fan is not a viable option. To the author's knowledge, no flight testing is forthcoming. Risk aversion has settled in – in sharp contrast with many of the case studies reported.

With regards to the CRP itself, modern designs feature clipped blades on the aft propeller, axial and radial blade sweep to improve load distribution and reduce noise [138], increasing axial spacing [116] and angular speeds, options to trim the CRP to unequal torque. The amount of optimal aft-blade clipping is a function of the aerodynamic load on the fore rotor. Too much blade clipping ends up over-loading the fore rotor and reduces overall propulsive efficiency. In terms of noise reduction, there exist a number of ideas, only tested in laboratory conditions. A summary of noise reduction ideas is provided in Ref. [139].

Scanning the technology trends in the 2020s, CRP are increasingly used for a variety of electrically-powered vertical take-off and landing (e-VTOL) vehicles. Unlike gas turbine engines, contra-rotation is achieved by electrical induction, which does not require mechanically complicated gear systems, is more compact, less prone to failure and possibly lighter. However, electromagnetic induction has been proposed for gas turbine engines [140], and that would appear to overcome some of the mechanical issues with contra rotation. Multiple lightly loaded single rotation propellers are likely to dominate electrical aero-propulsion in the coming years, where fixed-wing and rotary wing aircraft are concerned (NASA X-57 and Volocopter E-Volo, respectively). Highly loaded CRP have been applied to electrically powered VTOL prototypes: Airbus City Bus, EHang 116 and VT-30, Vertical Aerospace VA-X2 and Comac ET120.

11.0 Conclusions

The basis for the application of CRP has been the potential gain in mission performance; this was indeed achieved by pioneering designs. Mission performance is an issue that has come to scrutiny, which eventually identified several problems. Many of the prototypes indicated in our study were cancelled within one or two years, with only one or two airplanes having flown. Clearly, there were technological problems that are not always possible to solve. Projects before and around World War II were either seaplanes or highly powered single-propeller carrier-based military airplanes. Both disappeared because of changes in the world of aviation: The war was over, seaplanes became obsolete and the gas turbine engine became the dominant power plant. In the 1950s, the British industry achieved considerable success with at least two military aircraft that operated until the late 1970s and into the 1980s; yet, it also suffered spectacular setbacks with large-scale commercial projects that were driven by political pressure.

Each project, each flight test and each airplane identified unique problems: mechanical complexity of the contra-rotating hub and the gas turbine engine, forced vibrations on the aero structures (including propeller flutter and fatigue damage), and outright failures (gearboxes, lubrication and oil leakages).

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In the 1960s, CRP became successful in the Soviet Union, where a number of unique transport and military airplanes were developed. A few of these airplanes are still flying today. These airplanes fulfilled a specific need (long-range cruise) and matched the availability of an extremely powerful turboprop engine to a variety of different platforms.

In the Western World a number of flying prototypes using advanced prop-fans were developed, including several laboratory and scale models. It is commonly reported that the drop in oil price in the early 1990s caused the shelving of these and other CRP projects. In fact, this is not the whole truth. Lower oil price was an obvious escape from a propulsion concept still riddled with problems, many of which have not been solved to this date. The contemporary development of the high by-pass turbofan engines saw the demise of the large turboshaft engine for fixed-wing airplanes.

It has now been established that the increase in propulsive efficiency is achieved at a cost of multiple engineering problems. These include cabin and community noise, safety and airworthiness, public perception and acceptance, aircraft-engine integration, reliability, maintenance and direct operating costs. There are additional technological difficulties with the structural design and manufacturing of the blades, the blade containment strategies, the fluid cooling systems, and the reverse thrust.

The industry currently declares that the new open rotors are not yet mature to be considered for certification. If sustainable fuels will become more widespread, then the life-cycle emissions of CO_2 will be reduced; this scenario will likely divert efforts from further developments of the CRP because lower emissions can be achieved with proven power plants at a lower production cost.

At any rate, the technical literature on the advanced CRP and prop-fan continues to be overly optimistic. One truth that can be extracted from this research is that after 100 years of trials, we are not close to having a reliable, economical and environmental CRP on any single commercial aircraft.

Acknowledgements. Tom Fey, of Arlington Heights, Illinois, contributed considerable historical materials from his decades of research on contra rotating propellers, also as part of his work for the Aero Engine History Society. Tony Pilmer, librarian and archivist of the Royal Aeronautical Society, provided vintage photographs from the archives of the National Aerospace Library at Farnborough: All these photographs are acknowledged. My student Ho Liu contributed to the database shown in the tables. This research is funded by the UK Research Councils (EPSRC) programme Methods and Experiments for Rotorcraft, Grant EP/S010092/1.

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Cite this article: Filippone A. (2023). Historical development of the coaxial contra-rotating propeller. *The Aeronautical Journal*, **127**, 699–736. https://doi.org/10.1017/aer.2022.92