System-Modelling Approach for Counter-Rotating Open Rotor Aerodynamical and Aeroacoustic Performance Studies

Aleksandar Joksimovic (aleksandar.joksimovic@isae.fr)
Department of Aerodynamics, Energetics and Propulsion;
ISAE SUPAERO; 31000, Toulouse, France

The Counter-Rotating Open Rotor (CROR) jet engine configuration is historically known to have a significantly lower specific fuel consumption (SFC) than turbofan engines designed for the same mission. On the European level a rise in interest in CROR technology came as a consequence of an increasing social awareness of aviation environmental impact, followed by an organized international venture to reduce pollution both in terms of greenhouse gases and noise. In this context, the objective of the present work is to create a working performance model of a CROR configuration in PROOSIS™ software by means od public domain information exclusively. Firstly, the default PROOSIS library of components is assessed in terms of the extent of its utility for modelling a CROR. It is concluded that in this case, this library's capabilities are not applicable beyond modelling the engine core. Therefore, a development procedure of a planetary differential gearbox and a counter-rotating propeller is attempted and based upon available open source references. Having created and verified the new components to complement the default library for basic CROR modelling applications, a complete working configuration is compiled in PROOSIS. Furthermore, the results of steady-state simulations conducted on this configuration are used as a basis to define a design point similar to the one of a typical CROR which would power short/medium range aircraft. The final model is elementary, but from a qualitative point of view it is capable to produce consistent results and tendencies. This conclusion will be tested further with the upcoming development of the model for aerodynamical and aeroacoustic simulations.

Nomenclature

A	=	streamtube cross-section
C_{PWR}	=	power coefficient
C_T	=	thrust coefficient
D	=	propeller diameter
F	=	force
GR	=	gear ratio
J	=	propeller advance ratio
$\dot{m}$	=	air mass flow
N	=	rotational speed
P	=	power
r	=	gear radius
R	=	gas constant
T	=	thrust
T	=	torque
V	=	airspeed
Greek Letters		
η	=	efficiency
ρ	=	air density
ω	=	angular speed
Subscripts		
12	=	cross-section plane between two propellers
amb	=	ambient
C	=	carrier shaft
P	=	planet gear
P_1	=	the front propeller
R	=	ring gear/shaft
S	=	sun gear/shaft
TAS	=	true airspeed
Acronyms		
CROR	=	counter-rotating open rotor
HPC	=	high-pressure compressor
HPT	=	high-pressure turbine
PDG	=	planetary differential gearbox
SFC	=	specific fuel consumption

I. Introduction and Motivation

THE beginning of the new millennium witnessed an organized rise in European environmental awareness by both the airlines and the manufacturers embodied in ACARE and their objectives for aeronautics in the decades to come.[1] The outlined objectives have inspired a series of ongoing European international research projects and initiatives launched at the turn of the century with projects *EEFAE* and *SILENCER*. The EU projects are conceived to develop environmentally friendly engine technologies which target at significantly reducing local and global detrimental environmental impact of the civilian aviation, both in terms of polluting gas emissions and noise pollution.

Innovative technologies reflected in state of the art cycles and innovative components have been explored within projects such as *NEWAC* or *E-BREAK*. During the first decade the EU projects mainly focused on integrating these new discoveries into the traditional turbofan or its derived configurations such as triple shaft, geared, or counter-rotating turbofans. A major tendency was to increase engine bypass ratio and hence the propulsive efficiency. However, a drawback of the previously mentioned ducted configurations in terms of bypass ratio is that at after certain point it is not beneficial to increase bypass ratio as the SFC benefit gets cancelled by penalties in weight and friction drag (Fig.1).

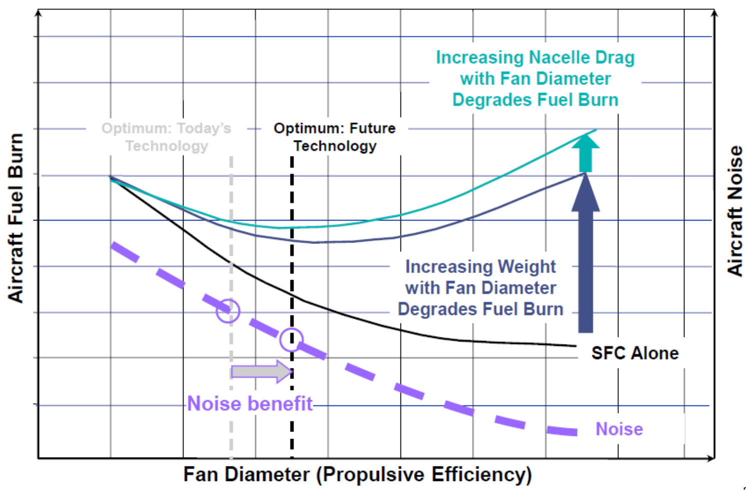

Figure 1. Engine Weight and Drag Impact on SFC for Increasing BPR.[2]

Counter-Rotating Open Rotor (CROR), an unducted configuration which operates at a practically infinite bypass ratio, was reintroduced through project *DREAM* and *Clean Sky* initiative as one of the most promising alternatives in terms of improved propulsive efficiency and fuel consumption. Following a dramatic oil price increase, CROR had been developed and extensively tested throughout the 1980's, when it demonstrated a potential to reduce the SFC compared with the turbofans of that time by 20-30%.[3] This improvement is a consequence of its ability to combine both the high propulsive efficiency of a turboprop with the speed and range capabilities of a turbofan. Despite these promising results and successful flight test campaigns[4], the interest in CROR diminished following a fuel price decline. Extensive efforts to deal with its intrinsic high noise levels and safety issues was no longer making CROR development worthwhile from the economic perspective.[5]

Given that the context of the EU research initiative is aimed at civil aircraft propulsion, the CROR configuration chosen for this project was a rear-mounted "pusher". This configuration had been demonstrated in the 1980s by GE and NASA (Fig.2), and the research on their GE36 "pusher" is well documented and available.[4,6]

The main reason for introducing a pair of counter-rotating propellers is that a single propeller imposes significant swirl energy to the airflow, which is lost in the wake. Reference 7 states that the efficiency loss due to this effect is of order of magnitude of 6-8%. By adding the rear propeller which rotates in the opposite direction, CROR is able to recover this swirl energy and thus produce more thrust with small energy penalty. The complex aerodynamical behavior of the two propellers is influenced by the engine nacelle, which is normally shaped to diffuse the flow speed in front of the propeller.[6] The engine installation structure, i.e. pylon and fuselage, introduce additional complexities to the aerodynamic behavior of CROR propellers.[8] Ever since the early days of this technology, the CROR blades have been characterized by a backsweep which enables the propellers to run efficiently at flight Mach numbers up to 0.8.[9] Currently, their tridimensional shape is more pronounced relative to the standards of the 1980s.

Figure 2. GE36 "Unducted Fan": a Rear-Mounted "Pusher" CROR Configuration.[5]

It is known that CROR engines have more important noise emission problems than ducted jet engines.[3,8,10] A breakdown of CROR noise sources[8] (Fig.3) suggests two principal types of sources: the core and the propellers. The former group consists of well studied sources common for conventional jet engines i.e. compressor, combustor, turbine and exhaust jet.[11] The propeller noise is more complex, being composed of several distinct components.

An extensive summary of experimentally verified acoustic features of a CROR configuration can be found in Ref.8, where an acoustic impact of different rotor-related parameters is studied. Interaction with the wake from the pylon is important for the noise generated by the front rotor, and it shows to be more pronounced at approach. It is shown that more swept blades generate less noise than the ones with a low sweep. Higher number of blades, which reduces aerodnamical blade loading, also results in noise level reduction. In combination with this effect, a clipping of the aft blades and having a different blade count on the two rotors proves to be beneficial. Increasing the distance between the two rotors is also beneficial in itself and in a combination with the rear rotor clipping. However, it is stated in Ref.10 that an excessive increase of the rotor interspace results in a degradation of the aerodynamical performance, which is why a compromise between the two must be found. Reference 3 presents a comprehensive theoretical model for CROR noise prediction. It puts an emphasis on distinction between aerodynamical and aeroacoustic interference: the former causing unsteady blade loading, and the latter enabling constructive or destructive addition of acoustic fields produced by each blade row separately. Some research indicates that the key aeroacoustic features regarding tone generation and the noise propagation are not dependent on blade design, despite the fact that modern blades have tendencies to generate significantly lower noise levels than the historic ones.[12] This observation proves to be important for the current work, given that the only open rotor propeller performance maps available in the public domain are representative of the blades developed in the 1980s.

In order to carry out propulsion performance studies, ISAE uses software called PROOSIS.[13] PROOSIS is a system-based turbomachinery modelling software written in an object-oriented programming language. The modular approach to turbomachine modelling is similar to the one found in NPSS™ software. PROOSIS was created through the EU project *VIVACE*, envisioned as means for providing the European industry and academia a standardized way of efficiently carrying out joint research on turbomachinery. The PROOSIS component library relevant for this work

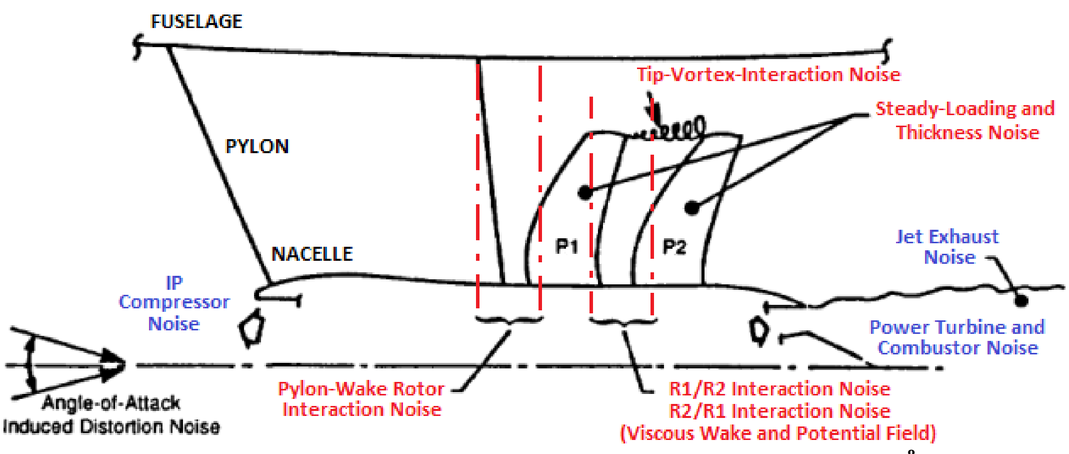

Figure 3. Typical CROR Noise Sources: Propeller (red) and Core (blue).[8]

is the default jet engine library called *TURBO*. It comprises all the standard components necessary to build complete models of traditional jet engine configurations such as turbojet, turbofan, turboprop or turboshaft.

The principal challenge for those who want to model a CROR is obvious: build a complete CROR using the TURBO library. If possible, this would ensure some robustness and reliability when modelling, and the effort could be directed towards problems different than upgrading the TURBO library capabilities. If this is not the case, an alternative path must be taken in order to account for this limitation, either by modifying the default library components or by creating new ones from scratch.

Previous work related to system-based CROR modelling was found in Ref.14 and Ref.15. Reference 14 introduces novel models of CROR-characteristic components in PROOSIS. The newly created counter-rotating propeller, gearbox and propeller are applied in a geared and a direct-drive open rotor model, and design point and off-design performance studies are conducted for both configurations. It was concluded that the developed technologies had to be further verified and improved, but that “the new simulation technique is a promising candidate for design space exploration and multidisciplinary assessments”.[14] Reference 15 presents similar work, performed in NPSS. In this study, basic modelling of the power turbine and the counter-rotating propeller is performed, based on the available GE36 data on those two modules. Multi-point design analysis enables a definition of a preliminary cycle, but it was concluded that if any quantitatively relevant results are to be obtained, updated data on CROR propulsor performance need to be incorporated in this type of study.

Apart from being motivated by the environmental objectives, the renewal of European CROR research initiative is supported today by a radical improvement in computational and design tools since the 1980s. Most notably, a capability to estimate unsteady blade loading is of major importance.[10] A direct implication of this is a widely accessible capability to tackle the previously mentioned intrinsic CROR challenges by basing new research upon the available material from the 1980s. Being aware of the situation and the industry tendencies, the Department of Aerodynamics, Energetics and Propulsion (DAEP) at ISAE SUPAERO launches an initiative to develop a CROR system model in PROOSIS. The first stage of the initiative, which is the subject of this paper, consists of creating a performance model which would represent basic aerodynamical and acoustic behavior of a CROR. From the modelling point of view, the initial work is dedicated to an assessment of TURBO library capabilities in terms of CROR modelling. If this approach proves to be unsatisfactory, the work will go on to building upon previous work in order to create a working model. Once a CROR configuration is assembled in PROOSIS, a design point and off-design behavior of the configuration will be defined. Taking into account PROOSIS capabilities and accessibility, as well as absence of any such effort in literature, another objective is attempted to upgrade the configuration with a noise prediction model. The goal of that part of the work is to enable general tendency estimations in terms of CROR noise, which could be used as guidelines for a more detailed research.

II. Modelling Using PROOSIS TURBO Library

The purpose of PROOSIS in this project is to meet the objective of building a working model of a CROR power plant, which will provide a capability to conduct design point and off-design calculations and performance analysis. The primary goal is to create a model using PROOSIS TURBO library components *exclusively*, which implies an attempt to utilize the TURBO propellers that are intended for modelling standard turboprops. Following a preliminary assessment of PROOSIS capabilities during the introductory phase of the project, it is observed prior to running trial simulations with TURBO propellers that there are no means at disposal to impose the opposite rotational sppeds to the turbine or propeller shafts. One could thus conclude that an attempt to model a CROR using TURBO library alone is failed at the beginning, but it is nevertheless considered as a valid option to attempt to use the TURBO propellers for the propulsor modelling if an alternative way to simulate a pair of counter-rotating shafts is found. The next course of action is therefore somewhat divergent from the original goal, but nevertheless necessary if any modelling at all is to be performed.

A. Planetary Differential Gearbox Development

The search for means of producing a counter-rotating double shaft output from a single shaft input resulted in creating a *planetary differential gearbox* (PDG), illustrated in Fig.4. A component which simulates a steady-state behavior of such a reduction mechanism is written in PROOSIS using Ref.14 and Ref.16 as basis. Aside from developing means to enable correct modelling of the

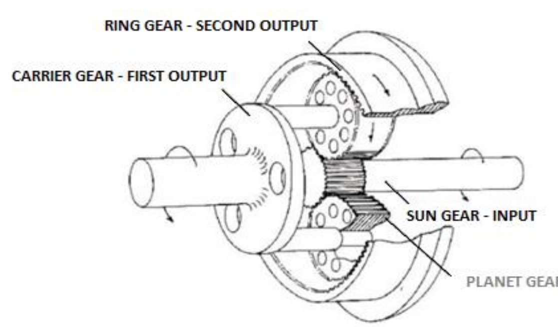

Figure 4. Planetary Differential Gearbox.[14]

preliminary configuration, an effort is made to provide the new component with an interface as similar as possible to the on of the TURBO gearbox. Aiming to reduce the risk of introducing numerical errors, some effort also goes into making the new system of equations as simple as possible, and as similar as possible to the one which describes the TURBO gearbox (Ref.13).

The starting point is a basic breakdown of PDG steady-state kinematics based on the free-body diagram presented in Fig.5. The force-torque equilibrium is used for deducing governing equations for the respective gears. The force and torque subscripts S, P, R, and C denote "Sun", "Planet", "Ring", and "Carrier" gears, respectively (Fig.4). In practical terms, the Sun gear is connected to the power turbine. Carrier gear, linked to the Planet gear shafts, is connected to the front propeller. The Ring gear is extended towards the shaft where the rear propeller is mounted.

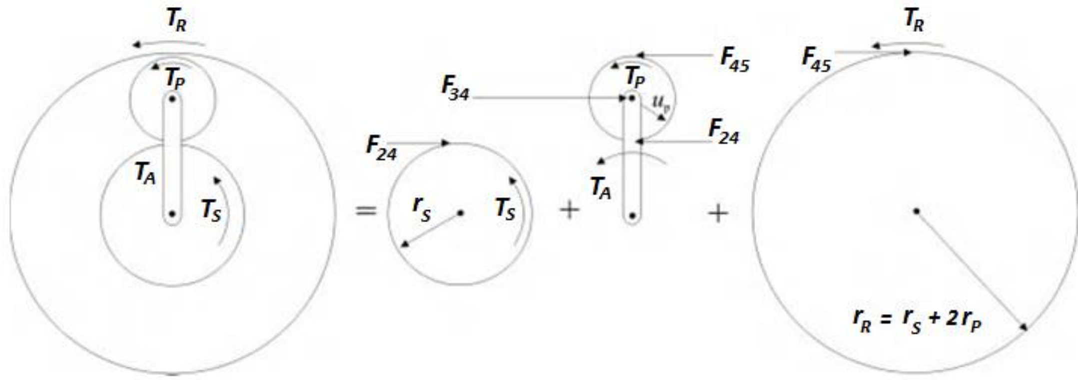

Figure 5. PDG Free-Body Diagram.[16]

$$T_S = r_S * F_{SP} \quad (1)$$

$$T_R = (r_S + 2 * r_P) * F_{PR} \quad (2)$$

$$T_C = -(r_S + r_P) * (F_{SP} + F_{PR}) \quad (3)$$

F_{PR} and F_{SP} are considered to be equal with an assumption of constant rotational speed for the planet gear.[16] If the Eqs. 1-3 are divided by each other all the system's respective torque ratios is found as a function of r_P/r_S. In addition, the energy balance used for calculating N_R is given by:

$$\eta * P_S = P_C + P_R \quad (4)$$

$$\text{with } P = \omega * T = \frac{2 * \pi}{60} * N * T$$

The final set of governing equations in the compiled PDG component is defined as follows (with *k* being an intermediate variable used for simplifying the component equation system):

$$N_C = GR * N_S \quad (5)$$

$$k = 1 + 2 * \frac{r_P}{r_S} \quad (6)$$

$$T_C = \eta * (k + 1) * T_S \quad (7)$$

$$T_R = -\eta * k * T_S \quad (8)$$

$$N_R = \frac{1}{T_R} * (\eta * T_S * N_S - T_C * N_C) \quad (9)$$

In contrast to the TURBO gearbox, the PDG is not steered only by the gear ratio. In order to obtain a desired gearbox output, the user needs to provide:

1) gear ratio: ratio of the power turbine and the first output shaft ("Sun") rotational speeds (Eq.5);
2) ratio of the planet and sun gear radii (Eq.6);
3) gear efficiency (Eqs. 7-9).

Given that the primary purpose of this project is to create a working PROOSIS model of a CROR, the effort is first and foremost concentrated on the component validation for steady-state calculations in order to be able integrate it into the engine model and calculate desired behavior for a design point case. For this reason, development of the PDG transient operation is left for future work.

The component is validated by running a steady-state calculation at first, followed by a parametric calculation to determine how the input parameters influence the two output rotational speeds. The results of the final steady-state simulation are compared with the ones from Ref.14. As it is presented in Table 1, the minimal obtained difference relative to the reference values is negligible for all practical purposes of the first approach modelling. Following this result, the PDG component is considered as validated for steady-state operation.

Table 1. Comparison of the PDG Steady-State Results to the Reference.

	Reference[14]	Calculation	% Difference Relative to the Ref.
η [-]	0.933	0.933	0%
r_P/r_S [-]	0.722	0.7391	+2.37%
GR [-]	1/5.95 = 0.16807	0.16789	-0.11%
N_S [rpm]	7600	7600	0%
N_C [rpm]	1276	1275.96	-0.0031%
N_R [rpm]	-1276	-1275.9	-0.0031%
T_R/T_C [-]	0.71	0.7125	0.35%
P_C/P_R [-]	0.585/0.415=1.409	1.404	-0.36%

The next step is to integrate the component into a complete system and validate its behavior in the integrated environment. The system would be a CROR-like configuration, with two standard components playing the role of CROR propellers.

B. TURBO Library Configuration with Two Default Propellers

The TURBO library CROR model is composed of the following modules (Fig.6):

1) a single-spool HP core: The idea is to have a preliminary representation of the overall core behavior, and to avoid introducing double-shaft cores. This would imply a more complicated simulation, which would divert the work effort from achieving the primary goal;
2) the power turbine system: represented by a TURBO library turbine and the newly developed gearbox;
3) a pair of TURBO propellers: to represent the counter-rotating rotor;
4) an exhaust nozzle.

The compressor and turbine components used in the schematic are without any performance maps. During the initial phase of the project there had been no a priori reference or target CROR cycle to aim for, which means that there was no way to design the component maps in PROOSIS* before the model was completely defined. Therefore,

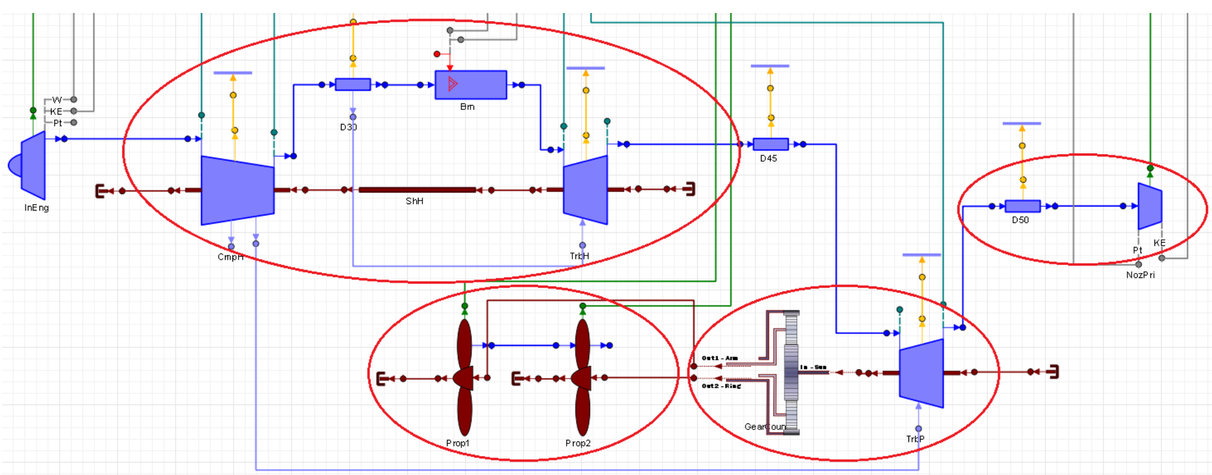

Figure 6. TURBO Library Approximation of CROR and Its Four Modules.

* In broad terms, PROOSIS compressors and turbines have default component maps which can be scaled in order to represent behavior of the configuration of interest. In order to do this, an appropriate design point must be provided.

it is decided to firstly build a model without compressor and turbine performance maps to steer its behavior, and once the iterative process of modelling and choosing appropriate cycle parameters is completed, to move on to designing the maps. The approach is ultimately retained throughout the entire project, while keeping in mind that the map design is something to be done during the next phase of the overall CROR research initaiative.

The absence of maps in PROOSIS can be compensated for single-design point simulations by properly choosing boundary values that correspond to the target operation point. A series of trial and error calculations is thus conducted for the created configuration in order to find a design point typical for an engine powering a short/medium range aircraft. The final set of boundary values assigned to the TURBO configuration is presented in Table 2.

Table 2. Boundary Values for the TURBO Library Model.

Fuel Mass Flow	[kg/s]	**0.321**
Inlet Air Mass Flow	[kg/s]	**17.5**
HPC Rot. Speed	[rpm]	**13000**
HPC Pressure Ratio	[-]	**18.55**
HPC Pol. Efficiency	[-]	**0.9**
Power Turb. Pol. Eff.	[-]	**0.9**
Rear Prop. Air Flow	[kg/s]	**300**

Following extensive attempts to adapt the boundaries and the input parameters, the utilization of TURBO library propellers shows to be futile for simulating a CROR. The results produced by the two propellers and the gearbox are presented in Fig.7 to illustrate this conclusion.

Two factors are identified as principal obstructions for the current goal:

1) TURBO propeller maps: these component maps are not made to operate anything near the advance ratio, or equivalently Mach numbers and rotating speed range of a CROR. Moreover, a CROR map is valid for a single Mach number only, which is not the case with the traditional propellers. An attempt is made to overcome the TURBO map limitations, so an open rotor propeller map is found in public domain. It was created experimentally by NASA in the 1980s.[17] The map is digitalized and inserted into the TURBO propeller models. Results of the repeated simulation imply the second difficulty.
2) the governing equations of the TURBO propellers: In order to read two separate maps for the two distinct propellers it is at least required for the airspeed to be somehow modified across the first propeller and then communicated to the second one in form of the entry speed. This however, is not possible since the TURBO propeller equations do not deal with speed of the traversing airflow, but only with pressure and temperature.[13] These parameters were not good enough to properly deduce speeds for the model. An alternative solution is to write a speed jump model and implement it directly into the default component. It is ultimately decided that it is more productive to direct this effort towards designing a new component specifically made to resemble CROR propellers.

The TURBO library of components was thus deemed incapable of modelling a complete CROR configuration, so another solution is going to be devised. The problematic part is to model the open rotor propellers, whereas the other modules can be suitably represented by the TURBO components. Consequently, the way to proceed is to keep the initial architecture unchanged, along with the new reduction gearbox component, and find a satisfactory way to replace the propeller module.

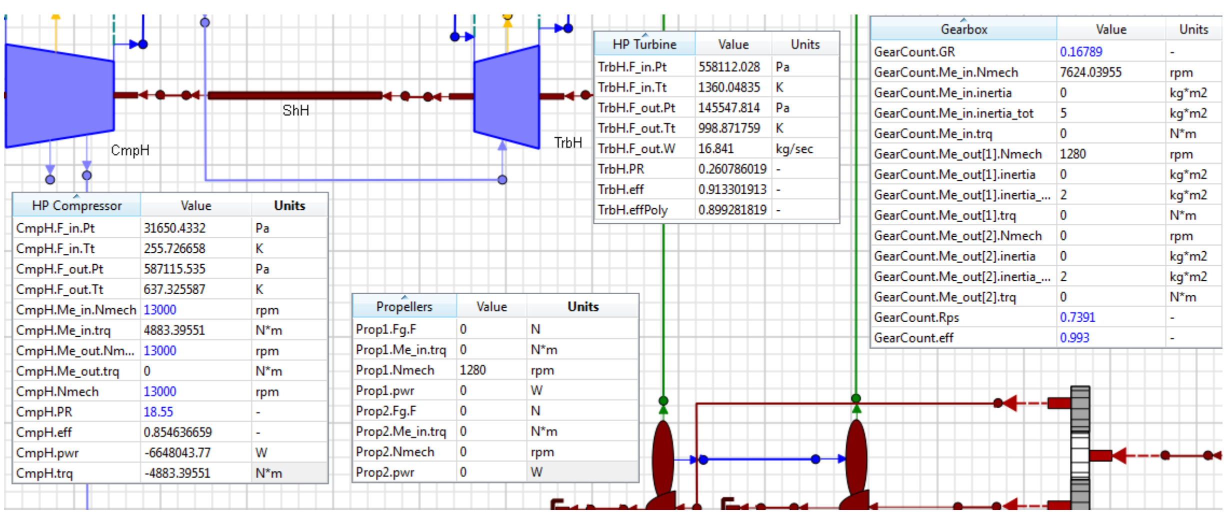

Figure 7. Typical Results for the TURBO Library Configuration: Null Rotational Speed and Torque Obtained for the PDG and the Propellers, and thus Null Thrust.

III. New Propeller Component and the Final Model

A. Counter-Rotating Propeller Development

In order to meet the need for simulating aerodynamical and aeroacoustic behavior of a CROR, a new model of the pair of counter-rotating propellers is written in PROOSIS, using results presented in Ref.14. Since an aerodynamically and aeroacustically optimal model requires that the two propellers have distinct features, performance parameters, and different influence on the acoustic signature of the whole machine, both propellers' respective governing equations are written separately within one PROOSIS component. At first, certain assumptions proved to be necessary[14]:

1) The two rotors' mutual aerodynamic influence is neglected. The front rotor operates with the inlet airspeed equal to the imposed flight speed. The inlet airspeed of the rear rotor is equal to the exit airspeed of the front one.
2) Inlet velocities of both rotors are purely axial.
3) Flow across the propellers is considered to be incompressible.

In terms of modelling, it is important to underline that both the propellers' performances are represented by one propeller map. The main reason for this decision is availability of representative open rotor propeller maps in the public domain. The only such maps found in public domain are the ones for historical "SR-7A" (NASA) and "F7/A7" (GE) blade sets. "SR-7A" is a single propeller map (used in Ref.14) whereas the "F7/A7" (used in Ref.15) represents the overall behavior of two distinct propellers, which does not suit the project requirements for the time being. Since the objective is to model two distinct propellers, as well as to have some reference to compare the results with, the "SR-7A" map is chosen to be used. Since a propeller map is valid for a unique blade geometry, this choice implies that until new maps are found, the two propellers in the model have to be considered as identical in terms of geometry. This decision will make the a posteriori acoustic simulations fall behind the current standards, but this will have to be dealt with at a later stage.

The map is discretized and written into an XML table readable by PROOSIS. It covers a range of Mach numbers from 0.45 to 0.90, a range of pitch angles from 57.7 º to 63.3º, and advance ratio ranging between 2 and 4.8. This means that performance at take-off (M = 0.2-0.25) is not possible to calculate by means of this model. However, the cruise Mach numbers of 0.7-0.8 and thus a preliminary single-design point dimensioning is allowed. In terms of utilization of the map, the propeller advance ratio is derived from the flight Mach number and the shaft rotational speed, imposed or calculated in PROOSIS. The propeller pitch angle is imposed as an input parameter of the new component. The propeller efficiency and the power coefficient are extracted from the map using the deduced advanced ratio and the flight Mach number. Although the two propellers use the same map, they operate at different regimes in terms of inlet Mach number, rotational speed and pitch angle, which results in distinct performance of the two propellers for a given flight condition.

Inspired by the result presented in Ref.14, a speed model across the first propeller is written using the actuator disk theory:

$$T_{P_1} = (V_{12} - V_{TAS}) * \dot{m} = (V_{12} - V_{TAS}) * \rho * A * V \tag{10}$$

$$P_{P_1} = \frac{1}{2}(V_{12}^2 - V_{TAS}^2) = T_{P_1} * V \tag{11}$$

$$\Rightarrow V = \frac{(V_{12} - V_{TAS})}{2} \tag{12}$$

$$V_{12} = \sqrt{V_{TAS}^2 + \frac{2 * T_{P_1}}{\rho * A_{P_1}}} \tag{13}$$

The airspeed expression in Eq.13 is obtained by replacing the expression for *V* (Eq.12) into Eq.10. It is simple and it is most certainly not representative of CROR propeller physical behavior in quantitative terms. Taking into account that the actuator disk theory can be corrected to account for compressibility, this description of the speed is sufficient to serve the purpose of creating a working baseline model which will be upgraded at a posteriori. The speed model update will imply a simple effort to replace the equation inside the component source code, without influencing the overall numerical behavior of the component.

The rest of the governing equations for this component come from propeller theory, and are written in the same form as they appear in the TURBO library propeller.[13] Note that within the final component each equation is repeated twice, for the two propellers, the only difference being their respective input values.

$$J = \frac{V_{TAS}}{D_{TIP} * \frac{N}{60}} \tag{14}$$

$$P = C_{PWR} * \left(\frac{N}{60}\right)^3 * D_{TIP}^4 * \frac{p_{amb}}{R * T_{amb}} \tag{15}$$

$$C_T = \frac{\eta * C_{PWR}}{J} \tag{16}$$

$$T = C_T * \left(\frac{N}{60}\right)^2 * D_{TIP}^4 * \frac{p_{amb}}{R * T_{amb}} \tag{17}$$

The input values for this component are the gear ratio, which represents ratio of the power turbine and the front propeller rotational speeds, the respective rotors' pitch angles, as well as the hub and tip radii. Knowing the pitch angle and the flight conditions, PROOSIS locates the efficiency and the power coefficient on the performance map. Necessary values of mass flows are calculated by means of continuity consideration through a cylindrical stramtube, which is defined by the propeller's hub and tip radii.

Contrary to the new gearbox, only a qualitative verification of the final propeller is carried out for the isolated propellers component. It is ensured by this verification that the equation system is consistent and the example calculations converge well. As opposed to the gearbox, the propeller performance is inseparable from that of the power turbine and the core and it is limited by the performance range of the chosen propeller map. For this reason, a quantitative validation of the component is to be carried out with the complete integrated system.

B. The Final Completed CROR Model in PROOSIS

With the new propeller and a gearbox capable of delivering a double counter-rotating shaft speed, the propulsor module of the TURBO-based model is replaced by a CROR-representative model, and the single-spool high-pressure core module is kept unchanged. This configuration is capable of running steady-state simulations (Fig.8).

In order to commence the experiment, a proper choice of boundary values must be made. Equivalently to the TURBO library modelling phase, this results in a series of iterations and trial experiments, especially due to the fact that the new propeller component behavior is to be verified within a complete system. Poor choices of boundary values results either in numerical divergence of the simulation or in converged results that do not make physical

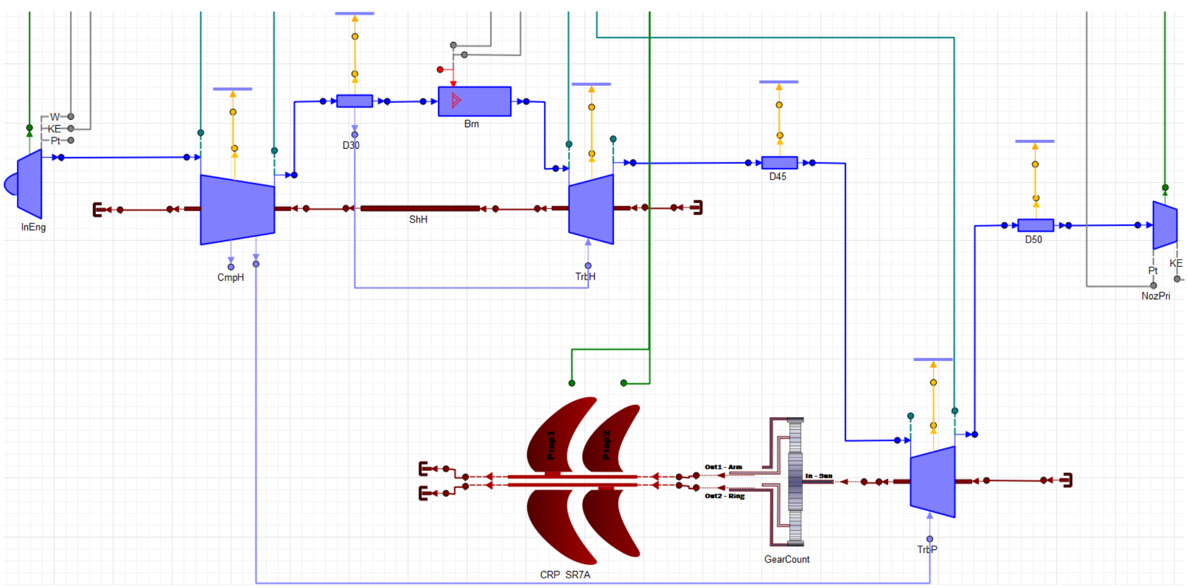

Figure 8. Final CROR Configuration with the New Propulsor Integrated.

sense. This trial and error loop is nevertheless less laborious given the similar experience with the TURBO model.

The final set of boundary conditions for the current CROR is given in Table 3. The mass flows and the rotational speed boundaries are based on Ref.14, whereas the high-pressure compressor pressure ratio and the polytropic efficiencies are estimated from common experience. In practical terms, choosing the air mass flow rate, polytropic efficiencies and the core rotational speed as boundary values allows a closure of the CROR model which does not have compressor and turbine performance maps at its disposal. Fuel mass flow is compulsory to define as it steers the energy input of the engine.

Table 3. Boundary Values for the CROR Model.

Fuel Mass Flow	[kg/s]	**0.321**
Inlet Air Mass Flow	[kg/s]	**17.5**
HPC Rot. Speed	[rpm]	**13000**
HPC Pressure Ratio	[-]	**18.55**
HPC Pol. Efficiency	[-]	**0.9**
HPT Pol. Efficiency	[-]	**0.9**
Power Turb. Pol. Eff.	[-]	**0.9**

IV. Choice of a Design Point

As it was done with all the calculations during the project, an assessment of qualitative properties of the results is made before going on to a quantitative evaluation. Remembering the previous experiences both with the TURBO library configuration and the new one, it is verified that the core and the propulsor behavior are not characterized by singularities, i.e. impossibly high rotational speeds or null power generated by the turbines. The gearbox is proved to consistently provide the desired speed reduction and power split. For the counter-rotating propellers it is verified that they both give contributions to thrust, and no singularities in power coefficients and efficiencies are present. The representative design point parameters chosen to be representative of cruise are fixed when a satisfactory compromise between available reference performance for the propulsor[14], and common experience for the core module, is found. The results are presented in Table 4.

Table 4. Definition of the CROR Model Design Point.

Component	Parameter		Value	Component	Parameter		Value
Ambient	Altitude	[m]	11000	Propellers	P1 Pitch Angle	[degr.]	60.1
	Flight Mach Nr.	[-]	0.72		P1 Rot. Speed	[rpm]	1175
	ΔTemp.ISA	[K]	+15		P2 Pitch Angle	[degr.]	58.5
Inlet	Air Mass Flow	[kg/s]	17.5		P2 Rot. Speed	[rpm]	-1175
HPC	OPR	[-]	18.55		Tip Radius	[m]	3.56
	Shaft Rot. Speed	[rpm]	13000		Root Radius	[m]	2.5
Burner	Fuel Mass Flow	[kg/s]	0.321		Bypass Ratio	[-]	18.89
HPT	Inlet Temperature	[K]	1411	Performance	Total Thrust	[kN]	22.57
Power Turb.	Rotational Speed	[rpm]	7000		P1 Thrust	[kN]	11.48
Gearbox	Gear Ratio	[-]	0.16789		P2 Thrust	[kN]	7.31
	Efficiency	[-]	0.993		Nozzle Thrust	[kN]	7.62
Nozzle	Exit Mach Nr.	[-]	0.866		SFC	[g/(kN*s)]	14.23

The design performance is very close to the results presented in Ref.14 for the geared configuration presented there. A disagreement is observed in the propeller rotational speeds, and in the nozzle thrust which is severely overestimated in the model presented here. Both the propeller rotational speeds and the nozzle performance are a function of the core parameters, so extra effort will be invested in the future project phase to refine the core model and define the absent component maps. The presented bypass ratio value seems to be very underestimated relative to what one would expect from an open rotor, which is also something to be aware of when creating an outline for the continuation of this CROR research campaign.

V.Conclusion and Future Work

The main objective of the project was to create a preliminary opeartional system-based performance model of a CROR power plant. Firstly, suitability of PROOSIS TURBO library was to be assessed and if it was proved to be insufficient for this purpose, an alternative solution was to be devised. The TURBO library proved to be well adapted to model the engine core and exhaust modules but the propulsor module, namely the counter-rotating propeller, had to be developed separately. Working models of a counter-rotating propeller and a planetary differential gearbox were developed and verified for steady-state simulations. An experimentally verified CROR propeller map was found in public domain, and it was integrated into the model. The new components were integrated into a CROR model and calculations were run until an acceptable design point was defined for the configuration. Time constraints did not allow for off-design performance definition and a component map design, nor for addition of an acoustic model. Nevertheless, a comprehensive state of the art review was provided in order to provide guidelines for future work.

The current model is not yet capable of producing quantitatively feasible results, but it makes a qualitative analysis of configurations representative of CROR possible. Its principal advantage is a capability to be easily adapted to better represent the current state of the art. Its two rotors are written separately within a single component, which allows individual assessment of the respective rotors' performance impact, while providing the necessary basis for future aerodynamical and aeroacoustic behavior assessment. The current propeller equations themselves are replaceable. With a more complete and up to date CROR map at disposal, the component can be modified to match current standards. With the defined design point defined it will be a matter of running several routine design calculations in PROOSIS in order to define performance maps for this configuration's compressors and turbines. A comprehensive study of the engine off-design behavior will then be possible

Remembering the ultimate goal of investigating CROR's potential to meet the society's environmental needs, the current model will provide a baseline, as well as means of preliminary qualitative analysis of performance tendencies, until the model is fully developed to enable a comprehensive CROR aerodynamics and acoustics simulations.

Acknowledgments

The author would like to express his most sincere gratitude to his family and his tutors who provided the only support a young engineer needs, unconditional trust, necessary guidance, and freedom to explore the unknown and use his talents.

References

[1]The Group of Personalities, "European Aviation: A Vision for 2020", ISBN 92-894-0559-7, 2001.

[2]Taylor, M., "Open Rotor Engine Design and Validation", *Royal Aeronautical Society Database*, URL: http://aerosociety.com/Assets/Docs/Greener%20by%20Design/%286%29%20Mark%20Taylor.pdf [cited 10 May 2014]

[3]Hanson D. B., "Noise of Counter-rotation Propellers", *Journal of Aircraft*, Vol. 22, No. 7, 1985, pp. 609-617.

[4]Harris, R. W., and Cuthbertson, R. D. , "UDF/727 Flight Test Program", *23rd Joint Propulsion Conference* [online database], URL: http://arc.aiaa.org/doi/abs/10.2514/6.1987-1733 [cited 18 June 2014].

[5]Hallion, R. P. (ed.), *NASA's Contributions to Aeronautics vol.1 – Aerodynamics, Structures, Propulsion, Control*, NASA, 2010, pp. 749,791.

[6]GE Aircraft Engines, "Full Scale Technology Demonstration of a Modern Counterrotating Unducted Fan Engine Concept, Design Report", NASA CR-180867, 1987.

[7]Zachariadis, A., and Hall. C. A., "Application of a Navier-Stokes Solver to the Study of Open Rotor Aerodynamics", *Journal of Turbomachinery*, Vol. 133, Issue 3, 7 Dec. 2010.

[8]Hoff, G. E. et al., "Experimental Performance and Acoustic Investigation of Modern, Counterrotating Blade Concepts", NASA CR-185158, 1990.

[9]Sullivan, W. E., Turnberg, J. E., and Violette, J. A., "Large Scale Advanced Prop-Fan (LAP), Blade Design", NASA-CR-174790, 1984.

[10]Peters, A., and Spakovszky, Z. S., "Rotor Interaction Noise in Counter-Rotating Propfan Propulsion Systems", *Journal of Turbomachinery*, Vol. 134, Issue 1, 24 May 2011.

[11]Hubbard, H. H. (ed.), "Aeroacoustics of Flight Vehicles Theory and Practice Volume 1: Noise Sources", NASA Reference Publication 1258, Vol.1, WRDC Technical Report 90-3052, 1991.

[12]Czech, M. J., and Thomas, R. H., "Open Rotor Aeroacoustic Installation Effects for Conventional and Unconventional Airframes", *19th AIAA/CEAS Aeroacoustics Conference*, Berlin, Germany, 2013.

[13]PROOSIS, Propulsion Object Oriented Simulation Software, Software Package, Ver. 3.2, Empresarios Agrupados Internacional S.A., Madrid, Spain, 2013.

[14]Bellocq P., Sethi V., Cerasi L., Ahlefelder S., Singh R., and Tantot N., "Advanced Open Rotor Performance Modelling for Multidisciplinary Optimization Assessments", *ASME Turbo Expo 2010: Power for Land, Sea, and Air*, Vol.1, Glasgow, UK, 2010, pp. 287-302.

[15]Hendricks, E. S., "Development of an Open Rotor Cycle Model in NPSS Using a Multi-Design Point Approach", *ASME 2011 Turbo Expo: Turbine Technical Conference and Exposition*, Vol.1, Vancouver, Canada, 2011, pp. 441-450.

[16]Dooner, D. B., *Kinematic Theory of Gearing*, 2nd ed., John Wiley & Sons, 2012, pp. 43-49.

[17]Stefko G. L., Rose G. E., and Podboy G. G, "Wind Tunnel Performance Results of an Aeroelastically Scaled 29 Model of the PTA Flight Test Prop-Fan", NASA TM-89917, 1987.