

Potential of Several Alternative Propulsion Systems for Light Rotorcrafts Applications

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ABSTRACT

Reducing greenhouse gas emissions to limit global warming is becoming one of the key issues of the 21st century. As a growing contributor to this phenomenon, the aeronautic transport sector has recently taken drastic measures to limit its impact on CO₂ and pollutants, like the aviation industry entry in the European carbon market or the ACARE objectives. However the defined targets require major improvements in existing propulsion systems, especially on the gas generator itself. Regarding small power engines for business aviation, rotorcrafts or APU, the turboshaft is today a dominant technology, despite quite high specific fuel consumption. In this context, solutions based on Diesel Internal Combustion Engines (ICE), well known for their low specific fuel consumption, could be a relevant alternative way to meet the requirements of future legislations for low and medium power applications (under 1000kW).

The objective of this paper is therefore to perform a detailed comparison between several propulsion systems for the particular application of a rotorcraft, taking into account realistic constraints (power to weight ratio, fuel economy...). Dedicated piston-engine architectures are first proposed, including 4-stroke Diesel technologies and turbocompounding. An evaluation of fuel consumption in realistic flight conditions is then performed using detailed ICE models coupled with a helicopter simulator. The use of Diesel ICE leads to consumption gains of the order of 40% but also increase the possible payload for long-range missions, compared to present turboshafts. The paper finally allows to draw perspectives of developments for future green rotorcrafts but also more generally for light and medium weight aeronautic applications.

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INTRODUCTION

Today, the transport sector is considered as one of the main contributor to the global warming and represented nearly 25% of the world's CO₂ emissions in 2011. In the last decade, decisions have been taken to aim ambitious reductions in terms of consumption, noise and pollutant emissions, needing thus major improvements in current propulsion system or the use of ground-braking technologies. For example, in the aeronautic field, the Advisory Council for Aeronautics Research (ACARE) wishes a reduction of about 50% for the CO₂ emissions of air transport before 2020 and about 65% in 2050 [1] in Europe. For low to medium power applications, like light-weight aircrafts, Unmanned Aerial Vehicles (UAV), Auxiliary Power Units (APU) or light to medium-weight rotorcrafts, whose maximal power does not exceed 1000kW, the specific fuel consumption of a Diesel

internal combustion engine (ICE) is, at least, 30-40% less than an equivalent gas turbine able to deliver the same power. Several research programs have thus been launched to develop such breakthrough technologies for air transport, like the CLEANSKY European initiative. Among the different works, one is about building engine demonstrators based on automotive and trucks know-how [2]. Combined with complementary technological breakthroughs such as electrification [3-4], potential benefits could then reach targets envisaged by the ACARE. Nevertheless, the specific development of ICE's adapted to aeronautic purposes is a very complex process during which simulations tools have a key role to play for highlighting the most promising paths to explore.

Besides, before the extensive use of turboshaft, the aeronautic sector was familiar to large ICE and developed several prototypes of an innovative system, which has been

later rehabilitated on ground vehicles and notably heavy duty trucks: the turbocompound. This device recovers energy available in the exhaust gases by an expansion through an additional turbine and delivers it to the crankshaft. The first appearances of such a device were the Curtis Wright R3350 in 1937 (a 18 cylinder 55L radial reciprocating engine [5]) and the Allison V1710-E22 (a 12 cylinder 65L, horizontally opposed 2-stroke Diesel engine [5]). If the second concept was not produced, the first one was highly used on the Douglas DC-7c and some versions of the Lockheed Constellation for instance, performing 3500hp (compared to 2700hp for the standard version used in the B29) and a best specific fuel consumption (SFC) of 325g/kWh at 60% power at 30000 feet [5]. More recently, Mercedes-Benz has developed the DD15 Diesel engine, a 6 inline cylinder 14.8L and 450hp, in which the turbocompound allowed an increase of 50hp and a 5% fuel saving. ICEs are commonly used for very light-weight rotorcrafts and research is nowadays oriented towards its use for larger helicopters and other kind of aircrafts [6]. A high energy density system such as the turbocompound may thus be an interesting complement for a standard ICE to fit the performances required in a rotorcraft application.

For this purpose, this paper deals with a comparison on several typical mission profiles (from mid to high-loaded and from short to long-duration mission profiles) between a classical turboshaft and two versions of the same four-stroke Diesel ICE, the second embedding a additional turbocompound system. The simulations allow determining the zone of interest for each propulsion system in terms of maximal payload, range and fuel consumption.

MODELLING

Engine Model

ICE design tools and methodologies have been mainly developed for ground transport purposes because it is the main technology used for propulsion on such systems. In this work, IFP Energies nouvelles (IFPEN) has recently adapted its tools to deal with aero-engines, especially regarding the specific technical specifications in this field, the combustion of Jet-A1 and basic flight simulations as well.

A target of 500 kW per engine has been fixed, considering a two-turbine helicopter of 2820 kg. On the base of standard ICE design rules, a 5.5 Litres and 10-cylinder four-stroke engine has been fixed to respect this requirement. Intake and exhaust architectures have also been a priori pre-designed using turbo-compressor matching tools. Detailed evaluation of the engine masses have been carried out to obtain reliable power to weight ratio.

Complete engine simulators have then been built using the IFP-Engine library available in the LMS.Imagine.Lab AMESim environment [7]. Such tools allow a detailed description of engine operation using a characteristic timescale of the order of the crankshaft angle. A variety of elements are available for modeling the different ICE

components, such as turbochargers, ducts, injectors and combustion chambers for instance. A particularity of this modeling tool is the combustion model which uses a highly detailed multi-zone combustion approach. This physical combustion model provides reliable boundary conditions for the engine air path components (compressors, turbines...) and is relevant to predict engine performance, efficiency and pollutant emissions on the whole engine operating conditions. This Diesel advanced combustion model (the Dual Flame Model, DFM) is based on the Barba approach [8] with major improvements based on IFPEN background added to the model. The DFM combustion model enables to compute the combustion heat release rate, taking into account the different phases of Diesel combustion (auto-ignition, premixed and mixing control combustion) and various injection strategies. DFM needs a slight calibration on test data to be representative. In this objective, single cylinder engine tests have been carried out using Jet-A1.

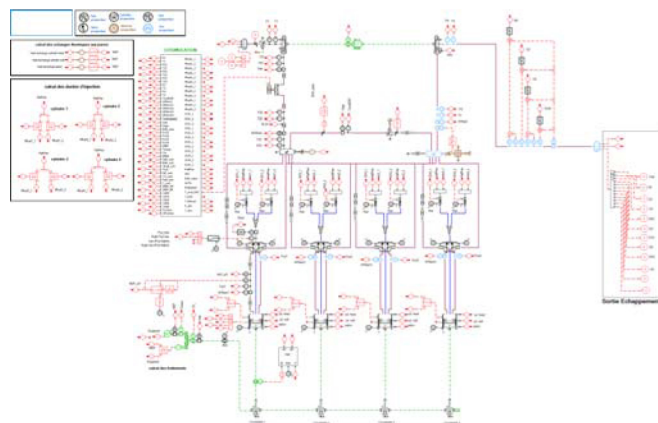


Figure 1. Example of an engine simulator sketch

In a last step, engine simulations have been performed for a wide range of operating conditions (low to full-power) considering different altitudes in terms of air pressure and temperature at the intake and exhaust. Parametric variations have been performed to estimate fuel consumption by taking into account thermodynamic and mechanical constraints on the system (maximum pressure in the cylinder and the different manifolds, maximum air/fuel ratio...).

Turbocompound

In addition, a turbocompound system has been added on a second version of the ICE to study the potential of such technology in light-weight rotorcraft applications, where the balance between engine power density and specific fuel consumption is highly meaningful. An analytic model has thus been plugged at the exhaust of the ICE simulator, allowing computing the recoverable energy, which is then reintroduced mechanically on the crankshaft. Two global efficiencies are taken into account to represent the turbine and the reduction gear. The equation for the recovered power at the exhaust considers an isentropic expansion hypothesis:

$$P_{TC} = \eta_{TC} \cdot C_{p_{GB}} \cdot \dot{Q}_{exh} \cdot T_{beforeTC} \left[1 - \Pi_{TC}^{\frac{1-\gamma}{\gamma}} \right] \quad (1)$$

with P_{TC} the recovered power, η_{TC} the turbocompound efficiency, $\dot{Q}_{exh}$ the exhaust mass flow rate, $T_{beforeTC}$ the exhaust temperature before the turbocompound, Π_{TC} the expansion rate through the turbocompound system, $C_{p_{GB}}$ the burned gases thermal capacity and γ_{GB} the heat capacity ratio for burned gases. In addition, $C_{p_{GB}}$ and γ_{GB} have been chosen constant, with the values of respectively 1290 J/kg/K and 1.33.

The recovered power is reintroduced on the crankshaft by the following relationship:

$$Torque_{TC} = \eta_{gear} \frac{P_{TC}}{N} \frac{30}{\pi} \quad (2)$$

with $Torque_{TC}$ the reintroduced torque, N the engine speed and η_{gear} the reintroduction efficiency.

As presented in Figure 2, the turbine is modeled by a variable orifice, whose maximal area has been arbitrary chosen quite large (3850mm²) to be able to study a large range of permeability (from 0.3 to 0.8). More extreme values have not been evaluated because with a too small permeability, the engine is no more able to reach the power objectives, and with a too large one, the turbocompound system becomes useless due to insufficient expansion.

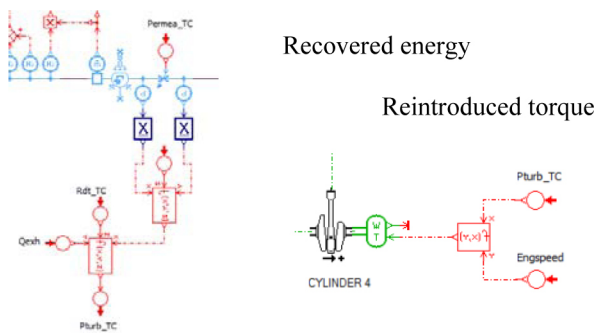


Figure 2. Turbocompound analytic model

The turbocompound concept performances have thus been evaluated by performing variations on permeability for two efficiency assumptions, one “reasonable” with efficiencies of 0.7 for the turbine and 0.85 for the reduction gear and one “optimistic” with respective efficiencies of 0.8 and 0.95. A wide range of operating conditions has then been simulated to explore the capacities of such a device to bring fuel consumption reductions.

If at low-load conditions, gains are not significant, simulations show a progressive and increasing potential reduction in fuel consumption when operating conditions evolve towards full-load, to reach a maximum of 8 to 10% according to the considered altitude. Even if these gains tend

to decrease when the rotorcraft is climbing, the power demand on the engines rarely goes under half-load, which allow the system to bring fuel consumption reductions in any tested conditions. However, the addition of a turbocompound impacts the engine total mass and the considered potential needs to be validate on flight simulations.

Rotorcraft Simulator

The four-stroke engine simulations results, with and without turbocompound, have been used to build specific fuel consumption engine maps which can be embedded in flight simulators (in the turbocompound case, the “optimistic” efficiency option has been considered to generate the maps). The evaluation of the different power packs are thus performed using a global low frequency approach which is based on the coupling between the engines map and a rotorcraft model describing two-dimensional (altitude/distance) missions. The impacts of the mass and the fuel consumption of the new propulsion systems have also been taken into account in the simulations in order to give a realistic estimation of the potential of these new concepts in this type of aircraft on different mission profiles.

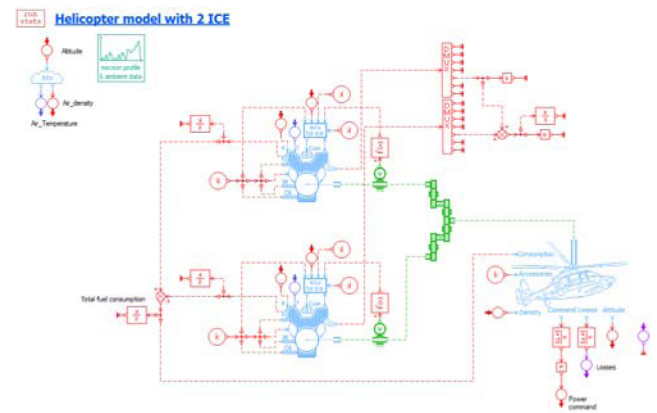


Figure 3. Rotorcraft simulator sketch

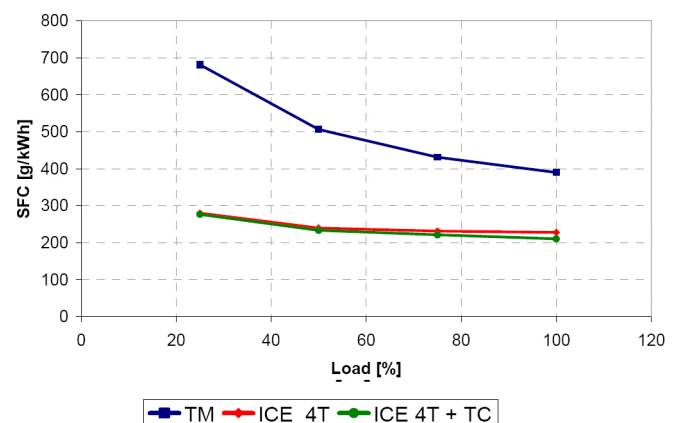


Figure 4. Specific fuel consumption for each power pack at altitude 0m and temperature ISA