

Assessing Environmental Benefits of Electric Aircraft Taxiing through Object-Oriented Simulation

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ABSTRACT

A number of promising technologies to perform ground movements without main engines are currently being researched. Notably, on-board ground propulsion systems have been proposed featuring electric motors in the landing gear. While such on-board systems will help save fuel and avoid emissions while on ground, they add significant weight to the aircraft, which has an impact on the performances in flight. A tool to assess the global benefits in terms of fuel consumption and emissions is presented in this work. A concept of an aircraft-integrated ground propulsion system is firstly considered and its performances and weights are determined, assuming the Auxiliary Power Unit or a zero-emission device like a fuel-cell as power source for the system. Afterwards, a model of the propulsion system integrated into an object-oriented, mid-sized aircraft model is generated, capable of precisely simulating a whole aircraft mission. Two different gate-to-gate flights with realistic trajectories are simulated with a conventional aircraft and one equipped with a ground propulsion system. Finally, the emissions and fuel consumptions are compared in each flight phase. The results show a potential overall fuel saving of up to 2.6%, depending on the flight mission and the duration of the taxi phases. The associated CO₂ emission may decrease by the same amount. Furthermore, NO_x, CO, and HC emissions on ground using an electrical taxiing system might be reduced by 64% to 80% compared to conventional ground operations. In conclusion, the aircraft model used in this work has proved a powerful tool to assess the performances of an electrical taxiing system and to compare different real-world scenarios.

CITATION: Re, F., "Assessing Environmental Benefits of Electric Aircraft Taxiing through Object-Oriented Simulation," *SAE Int. J. Aerosp.* 5(2):2012, doi:10.4271/2012-01-2218.

INTRODUCTION

Among the different flight phases, taxiing has a remarkable potential for reduction of environmental impact and fuel consumption. Aircraft normally travel between runways and gates using the idle thrust of the main jet engines, which are not fuel efficient in this condition and contribute significantly to noise and global emissions in the airport area. Idling engines particularly contribute to the CO levels because of incomplete combustion at idle [1]. As regards nitrogen oxides, aircraft ground operations accounted for an estimated 56% of the entire NO_x production at London Heathrow in 2002 [2]. While aircraft-related emissions only represent a modest share of all human activities (as an example, aircraft-related CO₂ emissions are 2% of the whole man-made CO₂ production [3]), the situation is going to worsen as world air traffic is expected to grow at a 4-5% average yearly pace, with an optimistic overall increase in the period 2005-2025 as high as 150% [4]. This will have a direct impact on airport capacities. U.S. domestic flights

experienced an increase in average taxi-out time by 11% in the period 2003-2007, while the average taxi-in lasted 9% longer over the same period [5]. Because of these trends, many airports face the need for an infrastructure expansion, but the environmental impact of airport activities often turns out to play a central role in the related social and political debates.

A number of systems have been proposed to reduce or avoid the use of main engines on ground. Taxiing with only one engine has been proposed, which, along with some benefits, also rises some technical and procedural questions [6,7]. As a matter of fact, most airlines opt for conventional taxiing with all engines.

Considering that a tug is needed for pushback, an intuitive solution would be towing the aircraft from the gate to the runway, a procedure known as dispatch towing. However, the practical implementation of this concept is not straightforward. Firstly, tractors should be powerful enough for appropriate performance. Secondly, they should be connected to the aircraft in a way that causes no mechanical

stress to the components as a towbar would. Finally, the technical and procedural issue of the pilot having to be in command during taxi needs to be solved [8].

The currently ongoing TaxiBot project is developing a prototype of a tractor for dispatch towing in which the mentioned issues are addressed [9,10]. Another concern about dispatch towing is that it would increase ground traffic, thus putting even more strain to the airport infrastructure.

As opposed to an external system like a tractor, on-board systems are also being developed. They usually feature electric motors integrated into the landing gears. As regards the power supply, using the auxiliary power unit (APU) is often considered an interesting solution. It is relatively easy to implement technically and is expected to offer significant benefits, because the APU is a smaller jet engine working near its best efficiency point compared to the main engines at idle. One early prototypical realization of such a system was WheelTug in 2005 [11], featuring two Chorus Motors machines mounted in the nose gear and supplied by the APU. More recently, some concurrent research projects are studying and developing similar solutions. In 2011, the German Aerospace Center (DLR) demonstrated a system with electric motors and planetary gearboxes in the nose gear; the power source was a fuel cell mounted in the aircraft cargo bay [12]. Such a zero-emission system in a large airport like Frankfurt might potentially achieve a 44-ton CO₂ abatement and almost 100% noise reduction [13]. Safran, Airbus, the University of Nottingham and the DLR are also developing an on-board system featuring direct-drive permanent-magnet synchronous motors integrated in the main gears [14]. This project is part of the CleanSky Joint Technology Initiative funded by the European Union [15]. While integration into the nose landing gear is easier because of the absence of the brakes, motorized main gears are believed to offer better performances in critical traction conditions (e.g. wet or icy ground surface) since the main gears support most of the aircraft weight. Also, no mechanical gearboxes are needed in the direct-drive design, resulting in less complexity and less risk of failure. Conversely, a larger, thus heavier motor is needed to develop the required torque.

One of the topics in research on More Electric Aircraft (MAE) is to replace the APU by a more efficient and less pollutant power source, for instance a hydrogen fuel cell [16]. In addition to a ground propulsion system, this would virtually eliminate noise and emissions during ground operations.

The weight of an on-board ground propulsion system is a key factor. While taxiing without jet engines saves fuel and cuts emissions, a heavier aircraft will consume more fuel in flight. The overall benefit of such systems needs to be quantified. In [17], estimates were calculated for a mid-sized aircraft by using fixed reference parameters, like e.g. engine or APU fuel flow at idle as well as engine specific fuel consumptions at different operating conditions. Mission consumptions were calculated from those specific fuel flow

data by multiplication with estimated taxi times, flight times, and flight power. Considering three different scenarios, fuel savings between 1.1% and 3.9% were predicted if a ground propulsion system supplied by the APU was used instead of the main gears.

In this paper, a method and a tool to estimate the fuel savings and emission reduction using a ground propulsion system are presented. A dynamic, physical model of a mid-sized aircraft realized in the modeling language Modelica [18] is used to simulate two benchmark flight missions from gate to gate with three different aircraft: a conventional one, one equipped with a ground propulsion system supplied by the APU, and one with a ground propulsion system and a zero-emission supply like a fuel cell. The focus is on reproducing a real-world scenario with actual ground trajectories and flight profiles as well as realistic performances of such ground propulsion systems. Finally, the simulated consumptions and emissions will be compared.

SYSTEM ARCHITECTURE

Propulsion System

The first step is to define the characteristics of the ground propulsion system that will be modeled. The system features two electric motors, each of them connected to the external wheel of a main landing gear. It is not necessary for the purpose of this study to clarify if the system is direct-drive or if a reduction gearbox is provided. Throughout this paper, “motor” will mean the whole driving assembly composed by the electric motor and the reduction gearbox if provided, and all data, particularly the torque, will be referred to the assembly output (interface to the wheel).

A ground propulsion system that may be applied in real airport operations shall be modeled. As discussed in [8], this means that minimum requirements on the system performances should be fulfilled. For example, crossing a runway starting from standstill from a holding position can be identified as a critical situation. This maneuver must be accomplished in a short time to minimize the impact on takeoffs and landings. A maximum time to cover a certain distance starting from standstill can be required of the system, which ultimately translates into a requirement on the driving force and power. According to ICAO regulations, the minimum distance from a precision-approach-category III, code 4 runway centerline to the holding position of a crossing taxiway is 90 m [19]. In order to dimension the ground propulsion system, the more restrictive minimum distance of 115 m prescribed by the Canadian transport authority, Canada Transport [20], is considered. We define the requirement that the aircraft equipped with the ground propulsion system shall be able to cover this distance doubled, that is 230 m, on a flat ground in no more than 45 s.

The breakaway forces that must be overcome to move a mid-size aircraft like an Airbus A319 on a flat ground have been quantified in 6 kN through measurements in [12]. Once in motion, the rolling resistance drops below that value. We

conservatively assume a constant rolling resistance of 6 kN at all speeds. The maximum takeoff weight of an A319 is 75,500 kg. It is also assumed that the propulsion system has an ideal torque characteristic as shown in Figure 1. Setting $F_D = 25$ kN as maximum driving force and 200 kW as maximum system power and resolving the problem numerically, the time needed to cover the assigned distance is about 42.9 s. The power value of 200 kW is a maximum limitation on the APU power supply, as explained in the next section.

Torque

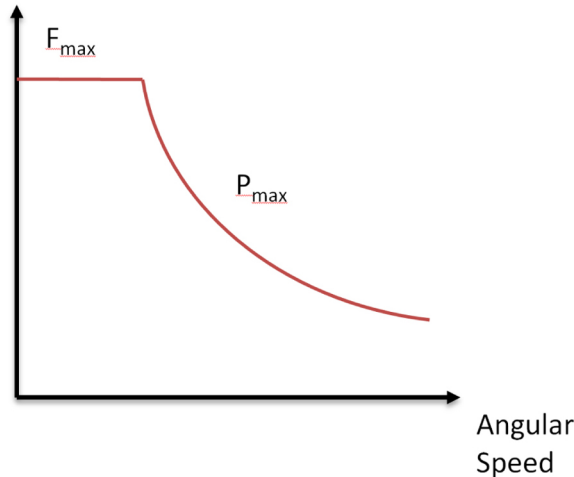


Figure 1. Ideal motor torque characteristic

Since the system has two motors, each of them has a maximum power $P_M = 100$ kW. Considering a main gear wheel radius $R_{MG} = 0.6$ m, the maximum motor torque will be $T_M = F_D \cdot R_{MG}/2 = 7500$ Nm.

As regards the weight, the requirement on the motor active mass in [14] is 75 kg. Based on this value, the weight of a single motor assembly with its associated power electronics control system is taken 200 kg for this work. Hence the system composed by two motor assemblies weighs 400 kg.

Power Supply

We want to simulate two different systems: the first one draws its power from the APU, while the second one relies on an independent power source.

Conventional APU Power Supply

We consider a Honeywell 131-9(A) APU which finds application in the Airbus A320 family as example of an APU for a mid-size aircraft [21]. This APU has a total nominal power of approximately 300 kW. The attached generator for the 115 VAC 400 Hz network has a maximum power of 90 KVA. The remaining 210 kW are used by the compressor for the air bleed system, which is used to start up the main engines and, depending on the aircraft, can supply other loads like the environmental control systems (ECS). Normally,

both the APU generator and the air bleed compressor are not at full power while taxiing, the engine startup procedure being by far the most power-demanding operation on the APU. It is therefore presumed that the APU can supply a power of 200 kW to the ground propulsion system. A dedicated, additional 200 kW generator should be connected to the APU gearbox. As regards the weight, a standard 225 kW APU generator weighs 71 kg [22]. Based on this, a weight of 100 kg is taken for the ground propulsion system generator in this work. The total additional weight due to the ground propulsion system is then 400 kg (for the motors) + 100 kg = 500 kg. The APU will need to be running when the ground propulsion system is operating, that is, during most of the taxi phase.

Zero-Emission Power Supply

Without further analyzing the nature and characteristics of the power source, a ground propulsion system will be assumed that is capable of driving the aircraft without any emissions. In a feasibility study for the Boeing 777, the weight requirement for a 440 kW hybrid APU featuring a solid oxide fuel cell and a conventional gas turbine is 880 kg [16]. By contrast, a conventional 300 kW gas turbine APU for a mid-sized aircraft only weighs approximately 160 kg [22]. However, such a hybrid fuel-cell APU for a mid-sized aircraft might be lighter than 880 kg since the required power is only 300 kW. Moreover, a system is assumed in this work having a fuel cell only, so the weight of the gas turbine should further be subtracted. As a conservative estimate, an additional weight of 700 kg for a mid-size aircraft equipped with a fuel-cell APU is taken. The weight increase of such an aircraft equipped with a ground propulsion system if compared to a conventional aircraft is then 700 kg (for the fuel-cell APU) + 100 kg (for the generator) + 400 kg (for the motors) = 1200 kg.

AIRCRAFT MODEL

The aircraft model has been realized in the Modelica [18] modeling language. It is an object-oriented, declarative language. Basic components and phenomena are modeled in a physical way within classes that are connected to each other through appropriate interfaces. This results in a more realistic and concrete modeling, in the sense that the sub-models of a system model ideally coincide with the components of the real system and different physical domains may be included in the same model.

The aircraft model is based on the Flight Dynamics Library, a library of aircraft components and physical phenomena related to flight that has been developed at the German Aerospace Center (DLR) [23]. Among other things, the library features:

- aircraft kinematics based on the World Geodetic System WGS84 standard,
- three-dimensional aircraft aerodynamics,
- jet engines including their dynamics,