An Object-oriented Model for Development and Assessment of Green Taxiing Systems

Fabrizio Re
DLR German Aerospace Center
Institute of System Dynamics and Control
Oberpfaffenhofen, Germany
Email: fabrizio.re@dlr.de

***Abstract*—A number of systems are currently being researched and developed that allow to move the aircraft on ground without using the main engines. The expected advantages lie in noise and emission reduction in the airport area, in optimization of energy use, and in simplification of driving and ground procedures. A 6-degree-of-freedom dynamic aircraft model with the new ground propulsion technology will be presented in this paper. The model has been realized in the framework of Cleansky SGO WP3.7 "Smart Operation on Ground" where a prototype of such a propulsion technology is being realized. The model is based on the object-oriented modeling language Modelica and is capable of simulating whole flight missions with particular focus on the ground phases. To this end, special effort has been dedicated in modeling the landing gear components, the tires, and the new propulsion parts with adequate detail. The model is a versatile and useful tool for several steps of the development process. Simulations of taxi phases help in the definition and revision of the performance specifications. Also, the overall benefit of the technology regarding emissions and fuel consumption can be assessed with simulations of whole gate-to-gate flight missions. Finally, the model can be used as virtual aircraft to design automatic control laws of motors, brakes, and steering system and to optimize the overall dynamic behavior of the aircraft on the ground.**

I. INTRODUCTION

Aircraft ground operations are one important source of emissions, as the conventional propulsion during taxi are the main jet engines at idle speed. In this condition, the engine efficiency is very poor and fuel is also wasted when no thrust is actually needed, e.g. when decelerating or stopping. In addition, idling jet engines contribute to a large part of airport noise.

Many drivers have led research to focus on environmental optimization of taxi. Increasingly strict environmental requirements on aviation such as the ACARE targets [1] as well as ever higher operating costs make it essential to exploit every unused potential for improvement of all flight phases. This is even more relevant for the ground phases as the current increasing trend in taxi-times is expected to worsen with the predicted air traffic growth and subsequent depletion of airport capacities. [2]–[4]

A number of projects are investigating and demonstrating alternate propulsion systems for ground movements. [5] One of these is Cleansky SGO "Smart Operation on Ground" [6], in which the DLR Institute of System Dynamics and Control takes part. The aim of the project is to build a prototype of an electric propulsion system integrated in the main landing gear of a narrow-body aircraft. In the framework of this project, a 6-degree-of-freedom dynamic aircraft model has been realized with the purpose of checking the consistency of the system requirements, testing the system performance and, in general, using it as a virtual aircraft equipped with a green taxi technology for subsequent studies and development. This model will be presented in this paper. Section II illustrates the fundamentals of the aircraft model. In section III, the models of the landing gears will be treated in more detail. Section IV illustrates the model of the propulsion system developed within Cleansky SGO "Smart Operation on Ground". Some examples of the use of this model will be given in section V. Concluding remarks are given in section VI.

II. AIRCRAFT MODEL

Since 1995, the DLR institute of System Dynamics and Control has constantly been developing a *Flight Dynamics* Library [7] that allows aircraft modeling in a realistic world environment at different levels of detail. The Library makes use of the open source modeling language Modelica, [8] which offers a number of advantages over other simulation environments. Most notably, Modelica is an object-oriented modeling language: model parts directly correspond to real components, resulting in more realistic modeling and more intuitive understanding of structures and interactions. Also, this principle is well suited for discipline-specific model libraries. The modular structure and the interaction of model classes through connectors with a physical significance make it easier to modify or expand a system model with reduced effort. Finally, the causality of the models is determined only upon compilation prior to simulation, allowing quick generation of inverse models with only few modifications in the declaration of model inputs and outputs.

The Flight Dynamics Library has already been used in a number of internal and international research projects (e.g. [9]–[11]), also being helped in this by the increasing diffusion of Dymola as standard simulation software in the aerospace industry.

A conventional aircraft model built with the *Flight Dynamics* library typically features at least the following components:

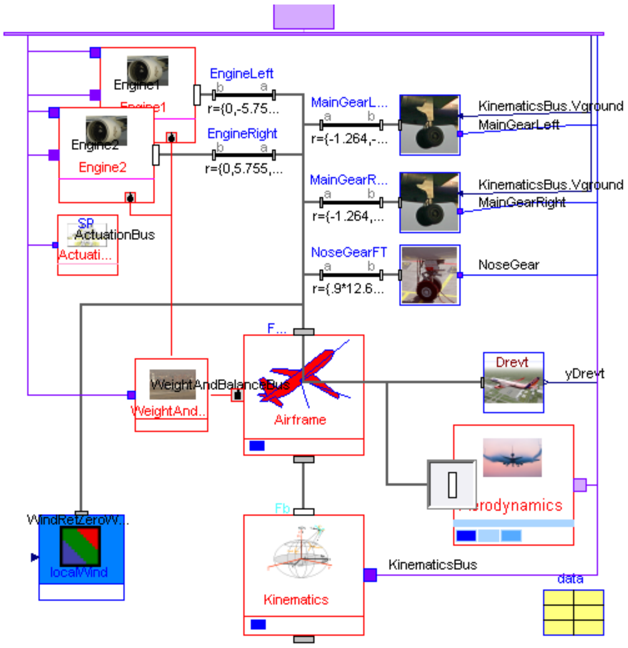

Fig. 1. Aircraft Model realized with the DLR *Flight Dynamics* library in the Modelica modeling language

- A **world model** providing the reference point of the Earth-Centered Inertial (ECI) frame, which will be the absolute reference system for the kinematics of all model components. Furthermore, the model provides a geodetic reference based on the WGS84 standard which results in an Earth-Centered Earth-Fixed (ECEF) reference frame; a model of the Earth gravitation based on the Earth Gravitational Model 1996 (EGM96) standard; a model of the Earth magnetic field based on the World magnetic Model from the US National Geo-Spatial-Intelligence Agency;
- an **atmosphere model** containing atmosphere data either as constant atmospheric conditions or according to the International Standard Atmosphere (ISA) as a function of height. Wind fields can also be implemented;
- a **terrain model** featuring models of the Earth surface with various levels of detail as well as functions for determining the latitude, longitude and height of any point in the absolute (ECI) reference frame;
- finally, an **aircraft model**. This is a structure of several submodels representing physical components (airframe, engines, actuators, sensors) and flight-relevant phenomena (kinematics, aerodynamics, wind). The submodels are linked together through physical connectors as well as a signal bus for exchanging variables across submodels. Various component models exist that can be combined to build different aircraft types, e.g. rigid versus flexible aircraft. Extensive parameter datasets for specific aircraft types are available for detailed simulation of aerodynamics as well as simulation of engine thrust and emissions in the whole engine operation range.

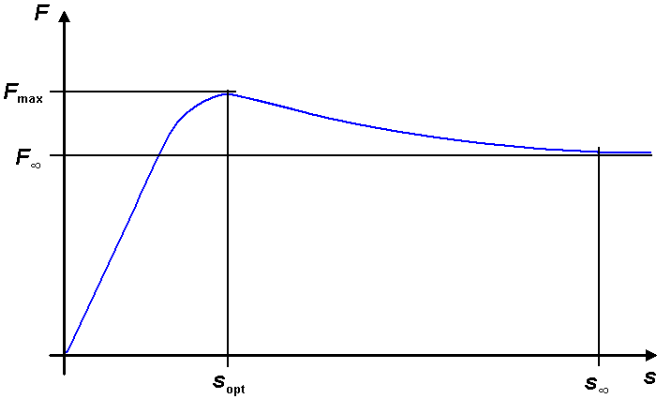

Fig. 2. Force over slip diagram of a generic tire

III. LANDING GEAR MODEL

During the Cleansky SGO ”Smart Operation on Ground” project, new landing gear models have been developed that allow detailed dynamic simulation of the aircraft motion on the ground.

A. *Wheel and Tire model*

The central element of the landing gear models is the tire model. Tires provide the necessary traction for controlling the aircraft on the ground and determine the dynamic behavior of the taxiing aircraft. Therefore they need to be modeled with high level of detail for the scope of this project.

A general-purpose tired wheel model library was already available at the DLR at the beginning of this work. The Modelica *WheelDynamics* library [12] is a set of parametric physical models of road vehicle tires with different levels of complexity. One of these wheel models has been picked and adapted for use in the aircraft model.

Figure 2 shows the basic force characteristic of the model, which is the typical behavior of a real tire. Such a characteristic qualitatively applies to both the longitudinal and the lateral direction. The force is a function of the relative slip between the tire tread and the ground surface, as well as on the vertical load and the camber angle. The dynamic curve shown is mainly influenced by the following parameters:

- optimum slip s_{opt} at which the tire force is maximum;
- friction coefficient at s_{opt};
- slip s_∞ above which the force may be assumed asymptotically constant;
- friction coefficient at s_∞.

All these parameters must be specified in pairs for the longitudinal and the lateral direction respectively. Also, the friction coefficients are dependent on the vertical load acting on the tire. To take this effect into account, two sets of parameters must be given with reference to two different vertical loads.

The tire model parameters were tuned through optimization against measurements data of real narrow-body aircraft tires made available by Safran MBD. These data contained several cornering force curves for different vertical loads for both main

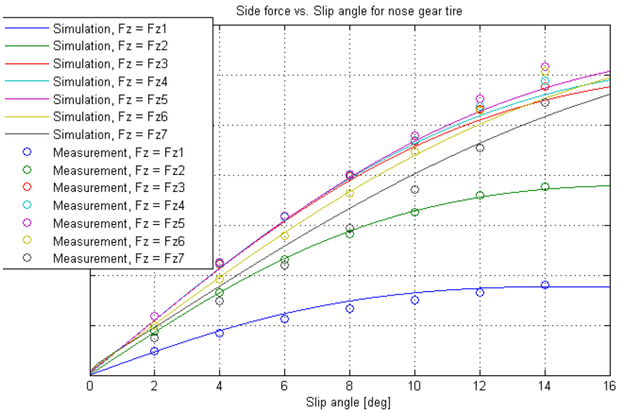

Fig. 3. Comparison between simulation and measurements of force-slip characteristics of a nose gear tire for different vertical loads

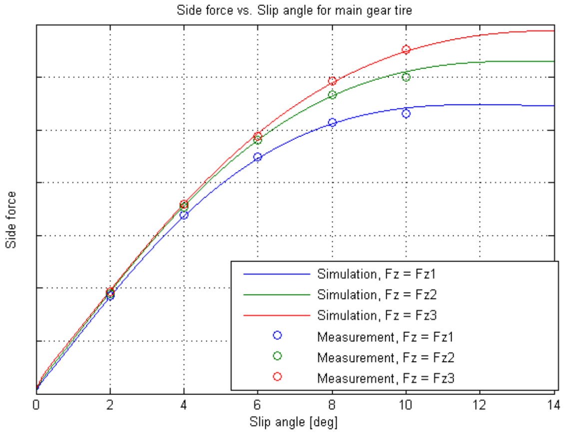

Fig. 4. Comparison between simulation and measurements of force-slip characteristics of a main gear tire for different vertical loads

gear and nose gear tires. Measurements were obtained from the provided diagrams for several slip conditions. A Modelica model of a test rig was created, including the tire model and with the possibility of imposing a vertical load, a velocity and a slip as inputs. The parameters were initially tuned with empirical values, and then an optimization process was carried out with the Dymola Optimization Library using the Pattern Search method. The results of this optimization with the comparison between simulation output and measurements is illustrated in Fig. 3 and 4.

A key aspect with regard to the simulation of the aircraft ground driving system is a realistic model of the tire rolling resistance. Measurements carried out by Safran MBD in the course of the project have shown that the rolling resistance in aircraft tires sensibly depends on the rolling speed, being the breakaway resistance (i.e. starting from standstill) generally greater than the rolling resistance at higher speeds. Also, the breakaway resistance itself increases with the standing time. The cause of this lies in the slow deformation of the tire under a vertical load applied on the same tire section for a long time. Therefore, the simple rolling resistance model based on constant coefficients was not sufficient and needed to be enhanced to reflect this behavior.

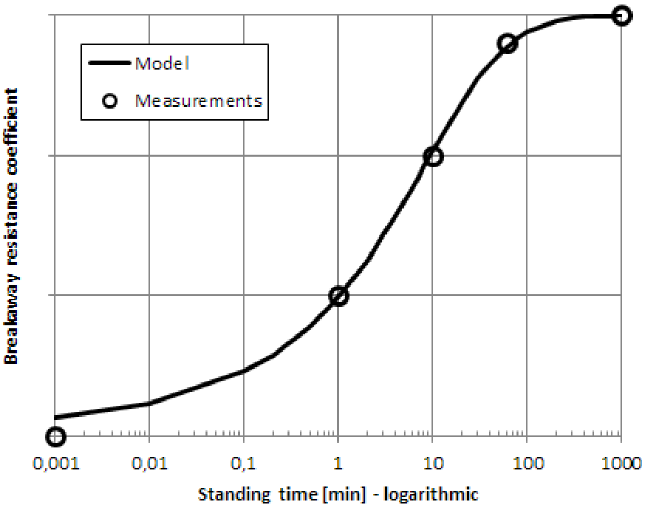

Fig. 5. Breakaway coefficient over standing time for aircraft tire model

From the analysis of the measurement data carried out on an Airbus A320, the breakaway coefficient rises with an increasing positive derivative at first up to a certain standing time, then with a decreasing one until an asymptotic value is reached. Then the following function of breakaway coefficient over standing time t, expressed in minutes, has been proposed:

$$\mu_b = \mu_{b,min} + \frac{\mu_{b,max} - \mu_{b,min}}{1 + \exp\left[m_b\left(-t^{p_b} + a_b\right)\right]} \tag{1}$$

This curve is based on the well known logistic function $f(x) = \left(1 + e^{-x}\right)^{-1}$, which has a characteristic S-shape with two asymptotes for $x \to -\infty$ and $x \to +\infty$. The tunable parameters $\mu_{b,min}$, $\mu_{b,max}$, m_b, p_b, a_b allow five degrees of freedom for shaping the curve. The asymptotic breakaway coefficient for large standing times was known from the measurements, corresponding to the parameter $\mu_{b,max}$. The other parameters were tuned with a least-square method using measurements of breakaway coefficient for different standing times. A comparison between the tuned curve and the measurements is displayed in Fig. 5.

B. *Bogie and Strut model*

The wheel model was used together with elements of the Modelica Multibody Library to build the landing gear models. Several variants have been realized: steerable two wheel bogie without brakes representing a nose gear (Fig. 6); fixed (non-steerable) two wheel bogie with brakes representing a main gear on small and medium aircraft (Fig. 8); and fixed (non-steerable) four wheel bogie with brakes representing a main gear on large aircraft.

The two-wheel types feature a vertical T-shaped structure, whose rods are Modelica *Fixed Translation* objects. The four-wheel type consists of a horizontal H-shaped structure connected to a vertical rod trough a rotational joint. The wheels

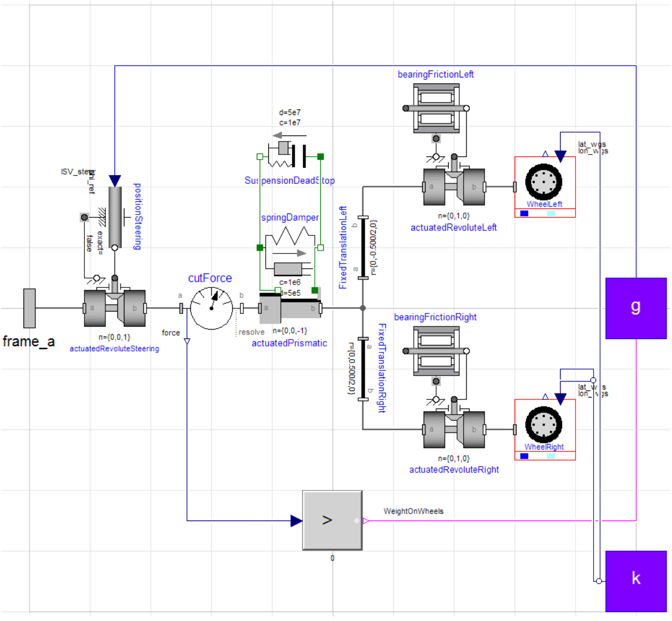

Fig. 6. Nose Gear Model

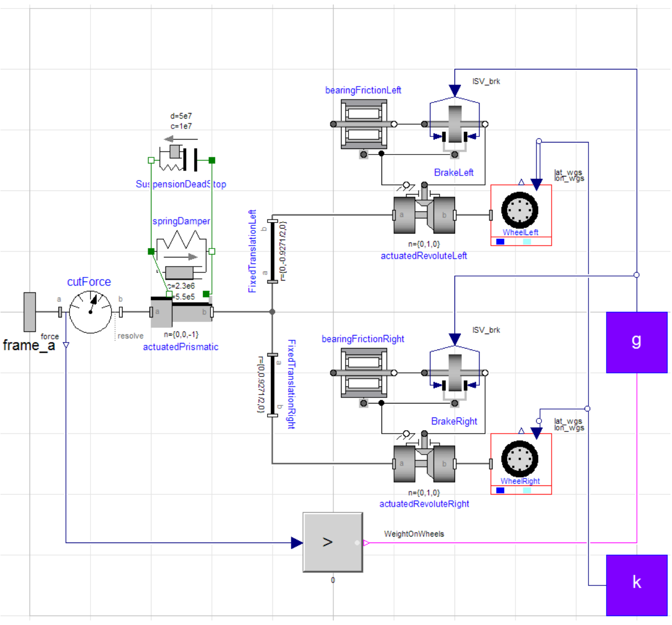

Fig. 7. Two-wheel Main Gear Model

are mounted respectively at the two ends of the T-structure and at the four ends of the H-structure. The vertical top end of the gear structure is connected to the airframe model through Modelica Multibody interfaces, which represent mechanical connections between tridimensional objects with exchange of forces and torques. *Fixed Translation* elements are placed between the airframe and the gear connectors in order to position the gears at the appropriate distances from the center of gravity. A suspension and a damper are also modeled between the gear structure and the body interface, with a simplified stopper to limit the suspension travel within the allowed range. All dimensional parameters can be adjusted to model landing gears of different sizes. A *Bearing Friction* block from the standard Modelica Rotational Library is connected to each wheel to model the frictional effects in the axle supports. In addition, sensors for detecting contact on the ground are modeled.

The steerable gear features a Rotational joint and an *Impressed Position* element to rotate the whole bogie around the vertical axis. The steering command given by the pilot is processed through a first-order block to reproduce the delays of real steering systems. This part may be replaced with a model of a real steering actuator for a more accurate dynamic simulation.

In the brakeable gears, brake elements from the standard Modelica Rotational Library are provided for each wheel. In addition, a simple ABS model was developed decreasing the commanded brake force appropriately to avoid wheel blocking. The braking signal applied by the pilot is read from the avionic bus, filtered through a first-order block accounting for real-system delays, processed through the ABS blocks, and finally given as input of the brake models.

IV. DRIVING SYSTEM MODEL

The ground propulsion system developed in "Smart Operation on Ground" comprises two controllable electric motors mounted on each external wheel of the main landing gears. Based on the direct-drive motor design carried out in the project, [13] a three-phase permanent magnet synchronous AC motor has been modeled. The model contains the dynamic equations of such a motor expressed in direct-quadrature axes, i.e. in the rotor magnetic field reference system: [14]

$$u_d = R_s i_d + L_s \frac{di_d}{dt} - p\omega L_s i_q \tag{2}$$

$$u_q = R_s i_q + L_s \frac{di_q}{dt} - p\omega L_s i_d + \psi_{PM} p\omega \tag{3}$$

$$T = \frac{3}{2} p \psi_{PM} i_q \tag{4}$$

where u_d and u_q are the voltages in direct and quadrature axis respectively, i_d and i_q are the currents in direct and quadrature axis respectively, R_s is the resistance of one stator phase, L_s is the inductance of one stator phase, ψ_{PM} is the flux of the permanent magnet, ω is the mechanical angular speed of the rotor, p is the number of pole pairs, and T is the motor torque.

The model input is the commanded phase current, whereas the output is the mechanical interface to the wheel represented by a Modelica rotational connector exchanging the values of angular velocity and torque.

A power electronics model supplies the current command to the motors. Assuming a direct current (DC) generator as power supply, the input of the inverter is a DC current, as well as the torque command desired by the pilot; the output is an ideal, sinusoidal three-phase AC current supplied to the motors. The fixed and the variable inverter losses are modeled by an additional constant current source and a resistance respectively. The current control strategy is field-oriented: [14] the phase currents are such that i_q is proportional to the torque command while i_d is zero at all times. No field weakening is applied.

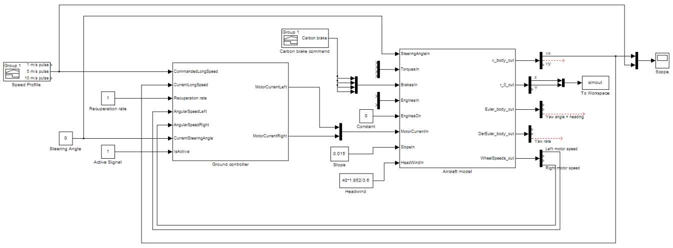

Fig. 8. Cleansky SOG speed controller with aircraft model used for test and assessment of the control law

The phases are strictly synchronous to the motor mechanical speed with a frequency $f = p\omega$.

V. APPLICATION EXAMPLES

Ground aircraft models based on the enhanced Flight Dynamics library can be used in a number of research projects, being an invaluable tool for simulation and analysis of the ground phases. Some current application examples of the modeling library described will be illustrated in the following.

A. *Cleansky SOG Ground driving control system*

In the scope of "Smart Operation on Ground", a speed controller has been designed to regulate the longitudinal motion of the aircraft electrically driven on the ground. The control system has been realized in Simulink. The Modelica aircraft model with electric ground propulsion was imported into the Simulink model by translating the Modelica compiled code into the Matlab MEX format (S-Function) and was used as plant for test and assessment of the control system.

The core of the ground control system is a PI-controller with anti-windup scheme for the longitudinal speed. The main inputs of the controller are the commanded target speed, the current longitudinal speed, and the current steering angle from the steering system; additional inputs are the upper and lower torque limits on both motors and a flag activating or deactivating the controller. The outputs of the controller gain are the commanded torques on each motor. These are limited to the maximum available motor torque at each instant depending on the motor speeds and on the conditions of the avionics and power supply system. When cornering, the commanded torques are modified with a static function of the nose gear steering angle in order to obtain differential moments that help the lateral motion.

The aircraft model introduced in this work has been used to validate the control law against the requirements by carrying out ground mission simulations. A taxi trajectory has been defined for this purpose, featuring backwards movements (substituting pushback), corners at different radiuses and speeds, and U-turns (Fig. 9). Since the Cleansky SOG controller is only restricted to the longitudinal motion, a steering controller was added to follow the trajectory, featuring open-loop control of the trajectory curvature and a proportional controller of the yaw angle (heading) for error compensation.

Through the data gathered by the simulations such as the speed and torque profiles shown in Fig. 10 and 11, it was possible to assess criteria like controller response and compliance with the required operating limits and ultimately pass the TRL3 gate on the control law architecture successfully.

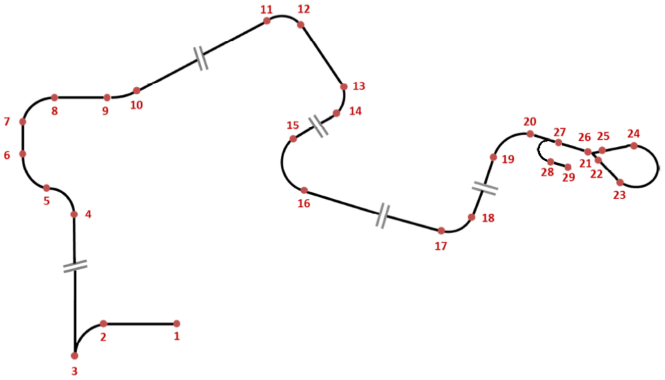

Fig. 9. Taxi trajectory used for test and assessment of the control law in Cleansky SOG

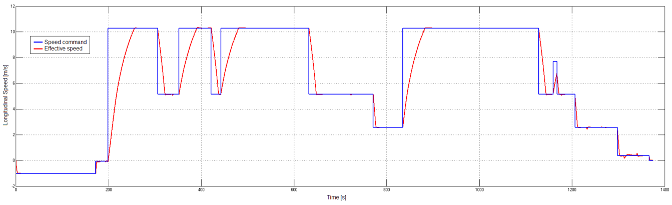

Fig. 10. Speed over time for test trajectory during the control system assessment of Cleansky SOG

B. *Research on optimal control system*

Further research is being carried out on more advanced control architectures. An aircraft equipped with more than one electric motor for taxi is an over-actuated system, as the same trajectory can be followed through different combinations of actuator commands. For example, cornering may be accomplished by combined use of the nose gear steering and differential moments on the electric motors. It stands to reason to optimize this control allocation for energetic efficiency and possible technical constraints of the system. An important step for this kind of studies is the possibility to use the aircraft model to realize a model-based control. In particular, inverse models can be generated easily starting from an object-oriented model. This has been demonstrated in [15] for the case of an aircraft with an electric taxi system. This allows to generate model-based control laws to cancel out the plant nonlinearities, a method called Feedback Linearization or known especially in the flight control community as Nonlinear Dynamic Inversion. [16] By their very nature, model-based controls with inversion of parametric models are very easily adapted to different aircraft and ground system architectures, making for quicker simulation, assessment, and comparison of different platforms and system specifications. To complete the control law, optimization criteria must be added such as finding the control allocation that minimizes the energy consumption over the whole taxi phase. Normative and technical constraints

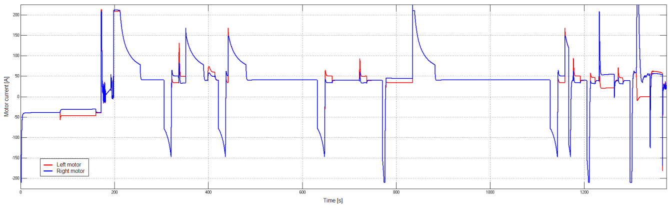

Fig. 11. Torque over time for test trajectory during the control system assessment of Cleansky SOG

should also be considered such as maximum taxi time, allowed amount of regenerative braking in the momentary system state, or thermal limitations on the system components.

C. *Assessment of environmental benefits*

An aircraft model similar to the one described in the previous sections was used in [2] to assess the environmental benefits of an on-board electric propulsion system over a whole gate-to-gate mission. While electric taxi is expected to save fuel while on ground, the flight efficiency will be lower due to the additional system weight, therefore the overall balance needs to be quantified. In the cited work, different gate-to-gate missions were simulated with a conventional aircraft and with an aircraft equipped with an electric taxi system. Detailed simulation was possible thanks to refined aerodynamic models as well as jet engine models calculating fuel consumption and emissions for every engine condition. In addition, a model of the Advanced Power Unit (APU) was realized for quantifying fuel consumption and emissions during taxi, as the APU generates power for the electric taxi system. The flight missions featured a taxi-out phase and a taxi-in phase as illustrated in Fig. 12 as well as a flight phase with different durations. Simulation results showed that for the chosen aircraft type and ground system, a total fuel saving of 2.6% was calculated for a 511 NM flight and a total fuel saving of 1.0% for a 864 NM flight. Also, a total reduction in CO emissions between 26% and 33% could be achieved along with a reduction in HC emissions between 43% and 47% over the whole flight mission. Finally, while the total amount of NOx emissions was unchanged, a relocation of the emissions occurs from the ground to the air, i.e. NOx emissions are cut on ground whereas they increase in flight by a similar amount. These figures show that the flight duration and the relative proportion of taxi phase and flight phase influence the result, but a substantial benefit can be expected in the case of regional or medium-range flights between busy airports.

VI. SUMMARY

The aircraft modeling activities in the framework of the Cleansky SGO "Smart Operation on Ground" project has been presented in this paper. Relevant components of aircraft landing gear and the electric taxi system have been modeled in the object-oriented language Modelica. The tire model has been especially tuned against measurement data for precise dynamic simulation of the aircraft motion on the ground. Beside the lateral tire dynamics, the breakaway friction (i.e. rolling friction starting from standstill) has been modeled in detail. The landing gear models and electric taxi system models are a substantial addition to the DLR *Flight Dynamics* library and may find use in research projects requiring simulation and assessment of the aircraft ground behavior and dynamics. Some applications examples have been shown to this regard.

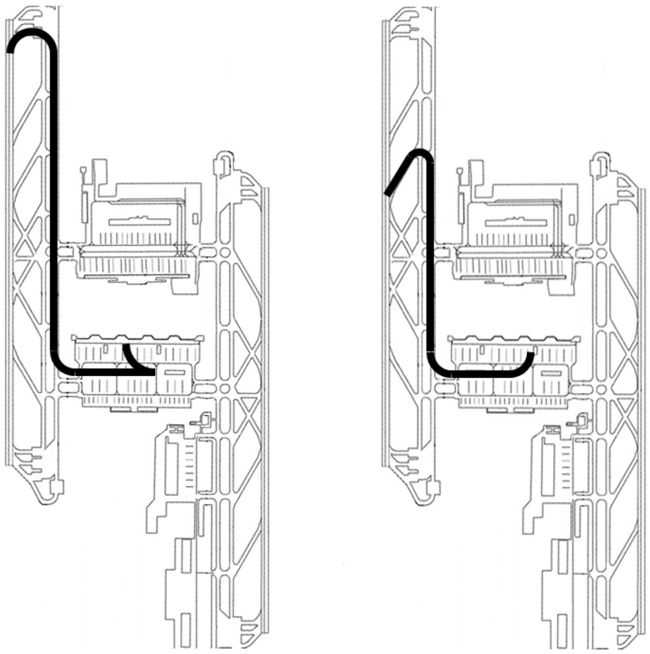

Fig. 12. Taxi-out (left) and taxi-in (right) trajectory used for assessment of environmental benefits of electric taxi systems

VII. ACKNOWLEDGMENT

This work has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) for the Clean Sky Joint Technology Initiative under grant agreement n CSJU-GAN-SGO-2008-001.

REFERENCES

[1] ACARE Flightpath 2050 - Europe's Vision for Aviation. [Online]. Available: http://www.acare4europe.com/documents/latest-acare-documents/acare-flightpath-2050

[2] F. Re, "Assessing Environmental Benefits of Electric Aircraft Taxiing Through Object-Oriented Simulation," *SAE International Journal of Aerospace*, vol. 5(2), 2012.

[3] "SESAR Definition Phase - Deliverable D1 - "Air Transport Framework, the Current Situation"," Tech. Rep., July 2006.

[4] Bureau of Transportation Statistics Special Report, "Sitting on the Runway: Current Aircraft Taxi Times Now Exceed Pre-9/11 Experience," U.S. Department of Transportation Research and Innovative Technology Administration, Tech. Rep., May 2008.

[5] F. Re, "Viability and State of the Art of Environmentally Friendly Aircraft Taxiing Systems," in *ESARS 2012 International Conference on Electrical Systems for Aircraft, Railway and Ship Propulsion*, Bologna, Italy, October 16-18, 2012.

[6] Cleansky Joint Technology Initiative Homepage. [Online]. Available: http://www.cleansky.eu/

[7] G. Looye, "The new DLR flight dynamics library," in *Proceedings of the 6th International Modelica Conference*, B. Bachmann, Ed., vol. 1. Bielefeld, Germany: The Modelica Association, 2008, pp. 193–202. [Online]. Available: http://www.modelica.org

[8] P. Fritzson and P. Bunus, “Modelica - A General Object-Oriented Language for Continuous and Discrete-Event System Modeling and Simulation,” *Simulation Symposium, Annual*, vol. 0, p. 365, 2002.

[9] J.-F. Magni, S. Bennani, and J. Terlouw, “Robust flight control - a design challenge,” in *Lecture Notes in Control and Information Sciences*. London: Springer Verlag, 1997, no. 224.

[10] G. Looye, “Integrated flight mechanics and aeroelastic aircraft modeling using object-oriented modeling techniques,” in *Proceedings of the AIAA Modeling and Simulation Technologies Conference*, Portland, USA, 1999.

[11] C. Fielding, A. Varga, S. Bennani, and M. Selier, “Advanced techniques for clearance of flight control laws,” in *Lecture Notes in Control and Information Sciences*. Springer, 2002, no. 283.

[12] D. Zimmer and M. Otter, “Real-time models for wheels and tyres in an object-oriented modelling framework,” *Vehicle System Dynamics*, vol. 48, pp. 189–216, 2010.

[13] T. Raminosoa, T. Hamiti, M. Galea, and C. Gerada, “Feasibility and Electromagnetic Design of Direct Drive Wheel Actuator for Green Taxiing,” *IEEE Energy Conversion Congress and Exposition*, 2011.

[14] J. N. Chiasson, *Modeling and High Performance Control of Electric Machines*. John Wiley & Sons, 2005.

[15] F. Re, “Automatic Control Generation for Aircraft Taxi Systems Through Nonlinear Dynamic Inversion of Object-oriented Model,” in *CEAS EuroGNC 2013 Conference, Delft, the Netherlands*, 10-12 April, 2013.

[16] G. Looye, “Rapid Prototyping Using Inversion-based Control and Object-oriented Modelling, in: D. Bates, M. Hagstrm (eds.) Nonlinear Analysis and Synthesis Techniques for Aircraft Control,” *Springer*, 2007.