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# Electrification studies of single aisle aircraft

## A 'retrofit' investigation including parallel hybrid electric propulsion

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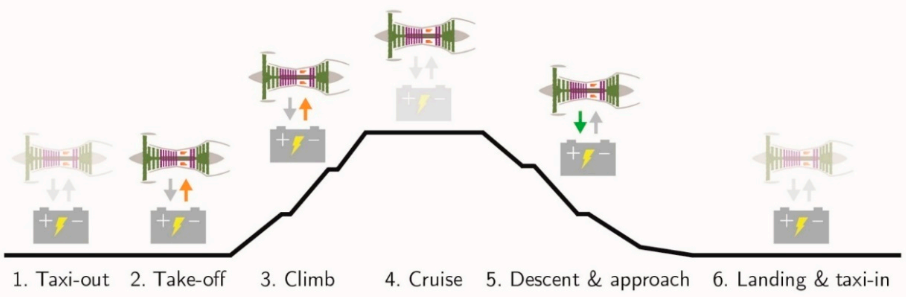

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### Problem area

Air travel has increased considerably over the past decades and it is expected to double in the next two decades. The combination of the rising demand for air transport and the need to decrease environmental impact of aircraft (exploitation of non-renewable fossil fuels, emission of greenhouse gasses and particles, and noise) put a strong challenge on the aircraft industry to come up with innovative technologies.

In the automotive industry hybrid and fully electric cars are rapidly developing in order to reduce environmental impact. In the aircraft industry, the fully electric propulsion has been introduced for light aircraft so far. The low power-to-weight and energy-to-weight ratios of electric components (in particular of batteries) hold back the development of fully electric commercial passenger aircraft. Nevertheless, Hybrid Electric Propulsion (HEP) systems may bring solutions, combining state of the art turbofan engines with innovative electric systems.

Another clear trend in aircraft design is the electrification of non-propulsive systems. More Electric Aircraft (MEA), e.g. the Boeing 787, feature advanced electrically powered systems instead of conventional hydraulic and pneumatic counterparts.

There is a strong interest to analyze the fuel and energy saving potential of HEP – e.g. in combination with the MEA approach - for single aisle passenger aircraft.

## Description of work

In the context of the EU Clean Sky 2 project NOVAIR a study was performed that focusses on a parallel HEP architecture in combination with electrification of the non-propulsive systems (the MEA-approach), 'retrofitted' to an Airbus A320neo reference aircraft.
The following main electric systems have been considered: electric motors, batteries and power electronics for parallel HEP, electric components for replacement of the main hydraulic and pneumatic non-propulsive systems and incorporation of fuel cell systems and photovoltaic cells for electric power supply. The power sizing of the electric components, as well as their mass effects on overall aircraft mission performance were evaluated by integrated system modelling of the aircraft, turbofan and the considered electric components

## Results and conclusions

A modular and parametric tool chain has been developed, for performance analysis of HEP aircraft for a given mission. In the current study an A320neo with 150 passengers on an 800 NM mission was evaluated. A parallel HEP architecture was applied to electrically support the turbofan engine only during the taxi, take-off and climb phases. The impact of various HEP modifications on a/c mass, fuel burn and total energy was analysed. Both near future (2020+) and far future (2040+) technology scenarios were applied. Fuel and energy savings up to 11% and 8% respectively were found with the 2020+ scenario. The 2040+ scenario gives respective fuel and energy savings up to 16% and 13%. The savings are mainly caused by reducing the engine core diameter and by the synergies of HEP, MEA and electric taxiing. Fuel cells and photovoltaic cells as applied here have only a very small effect.
HEP installation issues such as space, complexity, structure and thermal effects, and maintenance aspects, as well as costs were out of scope in this study. These items are envisaged for further research.

## Applicability

The parametric analysis tool chain allows for performance analysis of HEP aircraft for a given mission. The efficient models can be used for sensitivity analysis and optimization studies supporting the conceptual and multidisciplinary design of aircraft with HEP. It can also be used to analyse the effect of system modifications on existing aircraft in terms of mission performance.

**GENERAL NOTE**

This report is based on a presentation held at the International Symposium on Sustainable Aviation (ISSA), Budapest, 29/05/2019.

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# Contents

# ELECTRIFICATION STUDIES OF SINGLE AISLE AIRCRAFT: A 'RETROFIT' INVESTIGATION INCLUDING PARALLEL HYBRID ELECTRIC PROPULSION

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## SUMMARY

*This paper presents an investigation of the fuel- and energy-saving potential through the introduction of parallel hybrid electric propulsion (HEP) and more electric aircraft (MEA) approach on an Airbus A320 type aircraft. The following main electric systems are considered: electric motors, batteries and power electronics for parallel HEP, electric components for replacement of the main hydraulic and pneumatic non-propulsive systems and incorporation of fuel cell systems and photovoltaic cells for electric power supply. The power sizing of the electric components, as well as their mass effects on overall aircraft mission performance are evaluated by integrated system modelling of the aircraft, turbofan and the considered electric components.*

**Keywords:** single aisle aircraft, Airbus A320, hybrid electric propulsion, electrification, fuel cells.

## INTRODUCTION

Air travel has increased considerably over the past decades and it is expected to double in the next two decades (Airbus, 2018). The combination of the rising demand for air transport and the need to decrease environmental impact of aircraft (exploitation of non-renewable fossil fuels, emission of greenhouse gasses and particles, and noise) put a strong challenge on the aircraft industry to come up with innovative technologies.

In the automotive industry hybrid and fully electric cars are rapidly developing in order to reduce environmental impact. In the aircraft industry, the fully electric propulsion has been introduced for light aircraft so far (Brelje et al, 2018). The low power-to-weight and energy-to-weight ratios of electric components (in particular of batteries) hold back the development of fully electric commercial passenger aircraft. Nevertheless, Hybrid Electric Propulsion (HEP) systems may bring solutions, combining state of the art turbofan engines with innovative electric systems.

Various aircraft concepts involving several types of HEP were investigated before (NAS, 2016). These HEP types can be roughly divided into *serial* and *parallel* architectures. In serial architectures mechanical power is extracted from a thermal engine, converted to electric power and transferred to electric propulsors. In *parallel* architectures electric power is transferred from batteries and converted to mechanical power at the propulsor in addition to the thermal engine mechanical power.

Another clear trend in aircraft design is the electrification of non-propulsive systems. More Electric Aircraft (MEA), e.g. the Boeing 787 or Airbus A350, feature advanced electrically powered systems instead of conventional hydraulic and pneumatic counterparts.

In the NOVAIR project – carried out by TU Delft (Delft University of Technology) and NLR as part of the EU Clean Sky 2 (EU CS2, 2019) program Large Passenger Aircraft (LPA) – investigations on HEP for single aisle LPA are performed. One study focusses on a parallel HEP architecture in combination with electrification of the non-propulsive systems (the MEA-approach), applied to an Airbus A320neo reference aircraft. Previous results related to this study were recently published (Ang et al., 2018 and Tan, 2018).

This paper focusses on the effects of parallel HEP - with gradual system modifications - on the fuel consumption and overall energetic performance of the aircraft in a short-range mission of 800 NM with 150 passengers. The proposed system modifications include the downscaling of the turbofan engine, the application of electric taxiing, the conversion to an electrical architecture of the non-propulsive power systems, the implementation of a fuel cell system and the installation of photovoltaic panels on the outer skin of the aircraft. In the following sections, first the methodology including the involved models and analysis tool chain is described. Then the simulation assumptions and results are presented and discussed. Finally conclusions are given.

## ANALYSIS TOOL CHAIN

A modular and parametric analysis tool chain (see Fig. 1) was developed that simulates the performance of the aircraft (a/c), engines and electric system for a given mission.

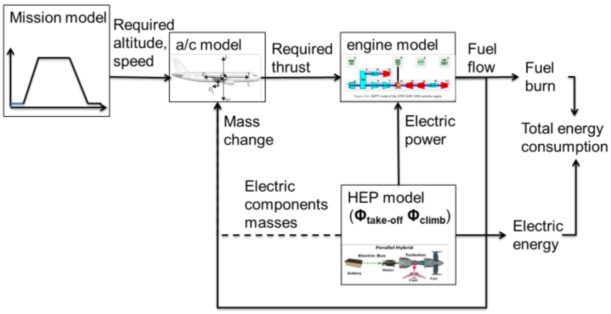

Fig. 1 HEP performance analysis tool chain.

Below the components of the tool chain are described.

The *mission model* reads an (Excel) table that contains the a/c altitude, speed, and flap and landing gear settings as a function of horizontal distance. An arbitrary mission can be inserted that fits in with the specified aircraft. In our case a mission with climb of 250 and 275 knots Indicated Air Speed (KIAS) and 0.78 Mach cruise was derived from (Airbus, 2002). The mission model calculates the flight path variables (altitude, distance, speeds, flight path angle etc.) as function of time.

The *aircraft model* takes as input the flight path variables in combination with a/c specific parameters (such as the a/c mass, and lift and drag coefficients as function of flap and gear settings and Mach number) and calculates the required thrust as function of time. The model is based on a so-called point mass representation of the aircraft. The equations below detail the calculation process of the thrust variable $F_N$. A flight path without horizontal curves is assumed. Changes in flight path angle $\gamma$ are approximated by (piecewise) circular motion (see Eq. 6). SI-units are applicable.

$$F_N = m \cdot \dot{v} + D + D_{ground} + m \cdot g \cdot \sin\gamma \quad (1)$$

$$\sin\gamma = \frac{\dot{h}}{v} \quad (2)$$

With $v$ true air speed (TAS), $h$ the altitude, $g$ the gravity constant, $L$ the lift force and $m$ the aircraft mass. The drag forces $D$ and $D_{ground}$ are calculated by

$$D = C_D \cdot {}^1\!/_2\, \rho \cdot v^2 \cdot S_w \quad (3)$$

$$D_{ground} = \mu \cdot N \quad (4)$$

With ρ the air density, $S_w$ the total wing area, $N$ the normal force ($N$=0 in the air) and $\mu$ the ground rolling friction coefficient (Airbus, 2002).

$$N = m \cdot g - {}^1\!/_2\, \rho \cdot v^2 \cdot S_w \cdot C_{L_0} \quad (5)$$

$$L = m \cdot v \cdot \dot{\gamma} + (m \cdot g - N) \cdot \cos\gamma \quad (6)$$

$$C_L = {}^{L}\!\Big/\!\left({}^1\!/_2\, \rho \cdot v^2 \cdot S_w\right) \quad (7)$$

$$C_D = C_{D_0} + kC_L{}^2 + \Delta C_{D_{flaps}} + \Delta C_{D_{gear}} + \Delta C_{D_{Mach}} \quad (8)$$

With $C_L$ and $C_D$ the aerodynamic lift and drag coefficients, $C_{L_0}$ the lift coefficient at zero angle of attack and $C_{D_0}$ the zero-lift drag coefficient, $\Delta C_{D_x}$ the drag coefficients dependent on flaps, gear and Mach number respectively, and $k$ the induced drag coefficient. The time derivatives $\dot{v}$, $\dot{h}$, and $\dot{\gamma}$ are approximated numerically.

The aircraft model and the mission model provide the required thrust and ambient conditions to the *engine model*. This model calculates the corresponding fuel consumption. It is a surrogate model derived from a CFM-LEAP-1a26 performance model created with NLR's Gas turbine Simulation Program (GSP, 2019). The surrogate model was created in order to achieve an efficient coupling with the aircraft model. A data set of 5300 steady state GSP results with 6 varied inputs was fitted using an artificial neural network algorithm. The resulting engine surrogate model predicts the fuel flow [kg/s], Low Pressure Turbine (LPT) shaft power [kW] and High Pressure Turbine (HPT) inlet temperature [K] as a function of altitude, Mach, required net thrust [kN], customer bleed flow fraction, LPT shaft offtake [kW] and engine diameter scale [%]. The outputs have a relative prediction error between 1 and 2 %, evaluated on a randomly chosen test set. The predicted fuel flow is used to calculate the total fuel burn [kg]. The fuel burn reduces the actual a/c mass and is fed back into the aircraft model after each time step.

A standard analysis with the tool chain consists of a mission simulation with the reference aircraft and then a repeat of this simulation with the electrified aircraft: the hybrid run. For this part the *HEP model* was created. To steer this model the *power split (PS)* ratio is defined:

$$PS = \frac{P_{EM}}{P_{tot}} \quad (9)$$

With $P_{EM}$ the power supplied by the electric motors to the engine shafts and $P_{tot}$ the total engine shaft power. In the current study parallel HEP is applied during taxi, takeoff and climb only. *PS = 0* during the other flight phases. The HEP model consists of interconnected submodels of the involved electric components like motors, inverters, cabling and battery, and optionally fuel cells and solar panels. These components are sized according to the required shaft power calculated by the engine model during the reference simulation run, the PS value, the required non-propulsive power as a function of flight phase and the assumed technology level. The resulting total (electric) system mass is added to the total a/c mass and provided to the aircraft model during the hybrid run. In addition, the power supplied by the electric motors as function of time and *PS* is provided as negative LPT shaft offtake [kW] to the engine model. During the hybrid run the total fuel burn and total energy are calculated. The latter is calculated by time integration of the total electric battery power in addition to the fuel burn multiplied with the fuel specific energy.

## ANALYSIS RESULTS

Fig. 2 shows results of a HEP performance analysis with the tool chain described above. The a/c altitude, true air speed (TAS), required thrust, fuel burn and total energy are plotted against the horizontal distance, both for the reference and the hybrid a/c. Note that the mission profile does not change between the reference and hybrid analysis run. A mission of 800 NM is evaluated with a payload of 150 passengers and 95 kg per passenger. Furthermore a fixed reserve fuel mass of ~1.8 t is assumed, accounting for alternate, contingency and reserve, estimated from (ICAO, 2010). This results in a reference a/c take-off mass of 67 t. Because the maximum take-off weight (MTOW) of the A320neo is 73.5 t (EASA, 2018) this leaves a ‘mass budget’ which can be filled with HEP components.

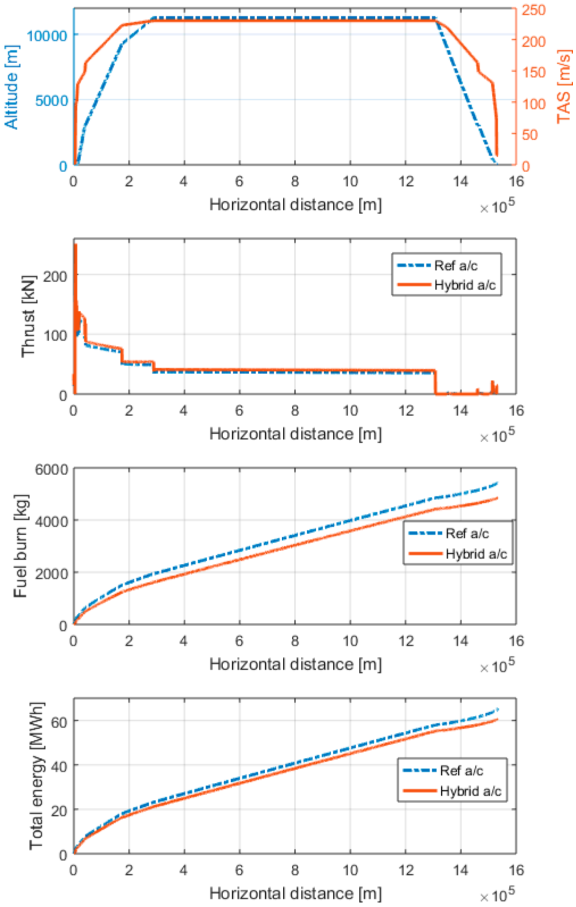

Fig. 2. Reference and hybrid a/c mission performance analysis results.

During the hybrid run PS values of 1, 0.15 and 0.1 are applied during the taxi, take-off and climb phases respectively. During the other phases the PS remains zero. This hybrid simulation applies all the HEP-related modifications: the core diameter of the turbofan engine (TF) is downscaled to 90%, a MEA architecture is used, a fuel cell system (FC) delivers a constant power of 300kW and photovoltaic (PV) panels on the skin of the aircraft deliver a constant 45kW. Both FC and PV are used to support the non-propulsive electric power consumption demanded by the MEA. The assumed non-propulsive power offtakes are listed in Table 1, both for the conventional and MEA architecture. These values were derived from (Scholz et al., 2013), (Chakraborty et al., 2015) and (Chakraborty et al., 2016). From the latter it was also derived that applying the MEA concept reduces the mass of the non-propulsive power systems with approximately 800 kg.

Table 1. Bleed and shaft off take values

| **Flight phase** | **Customer Bleed fraction** | **PTO [kW] per engine** | |
|---|---|---|---|
| | | **Conventional** | **MEA** |
| Taxi | 0.1 | 35 | 129 |
| Take-off | 0.03 | 37 | 128 |
| Climb | 0.05 | 42 | 176 |
| Cruise | 0.06 | 40 | 177 |
| Descent | 0.1 | 35 | 143 |
| Landing | 0.04 | 35 | 102 |

The reduction in fuel burn and total energy (see Fig. 2) has a strong dependency on the assumed technology level. A literature study was performed (Tan, 2018) with respect to specific energy, specific power and efficiency of the involved electric components. This resulted in 2020+ and 2040+ technology scenarios. The scenarios contain assumed averaged values (see Table 2) that could be applicable to Entry-Into-Service (EIS) aircraft between 2020 and 2040 or for EIS after 2040. A mass penalty due to additional cabling was not applied in this study. Furthermore it is remarked that for the PV system the efficiency is incorporated in the specific power.

Table 2. HEP Technology assumptions

| **Parameter** | **2020+ value** | **2040+ value** |
|---|---|---|
| Battery specific energy [Wh/kg] | 500 | 1000 |
| Battery efficiency [%] | 92.5 | 95 |
| Electric motor specific power [kW/kg] | 7.5 | 15 |
| Electric motor efficiency [%] | 95 | 98 |
| Inverter specific power [kW/kg] | 7.5 | 15 |
| Inverter efficiency [%] | 95 | 98 |
| Cable efficiency [%] | 99 | 99.6 |
| Fuel cell specific power [kW/kg] | 0.5 | 1 |
| Fuel cell efficiency [%] | 60 | 75 |
| Photovoltaics specific power [kW/kg] | 0.5 | 0.9 |

The results in Fig. 2 are based on the 2020+ scenario. Fig. 3 and Fig. 4 show the relative deviations in aircraft operating empty mass (mOE), total trip fuel (bFuel) and energy (bEnergy) of the HEP modifications with respect to the reference a/c, for the 2020+ and 2040+ scenarios respectively. Both figures show that the FC and PV as applied here have almost no effect. The reduction in fuel mass and energy is mainly caused by TF downscaling and by applying the MEA concept. As a consequence of boosting electrically during take-off, the TF core diameter can be reduced slightly, improving its sizing for the cruise operating point. This means that the TF can operate more efficiently during cruise. Furthermore the total engine mass is reduced, which affects mOE. Further downscaling of the engine core diameter to 80% gives a maximum HPT inlet temperature which exceeds the corresponding maximum value of the reference a/c with 200 K. In order to stay within the HPT inlet temperature range of the reference a/c, the 90% engine is applied with the other modifications. With the hybrid a/c configuration with all modifications and 90% engine applied, 11% fuel and 7% energy reductions were found, with the 2020+ scenario. The corresponding performance results of this configuration are also depicted in Fig. 2. With the same configuration in the 2040+ scenario fuel and energy reductions of 16% and 12% were found respectively.

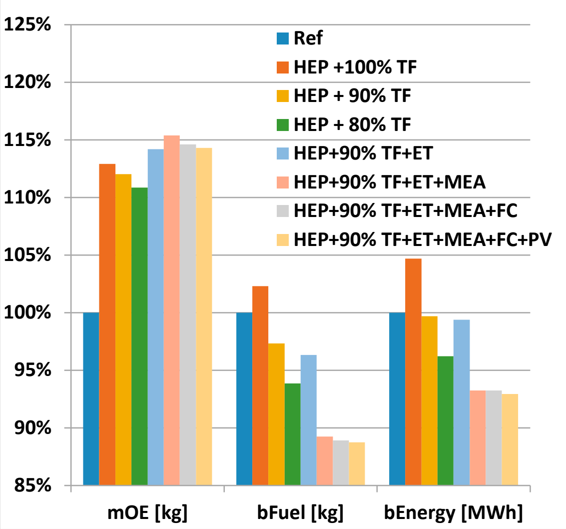

Fig. 3. Impact of HEP modifications with 2020+ technology scenario.

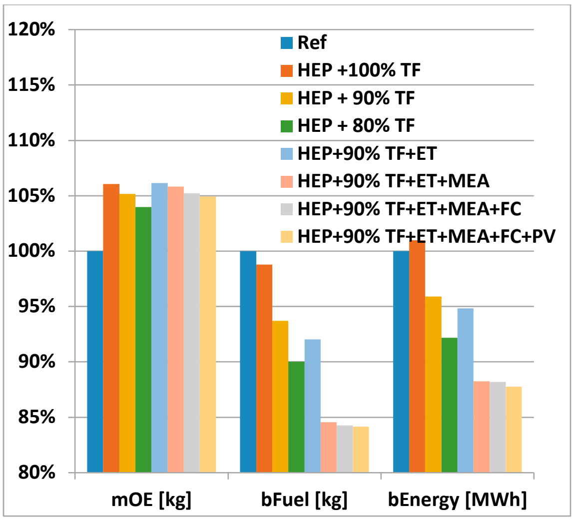

Fig. 4. Impact of HEP modifications with 2040+ technology scenario.

## CONCLUSIONS

A modular and parametric tool chain was developed for performance analysis of HEP aircraft for a given mission. In the current study an A320neo with 150 passengers on an 800 NM mission was evaluated. A parallel HEP architecture was applied to electrically support the turbofan engine only during the taxi, take-off and climb phases. The impact of various HEP modifications on a/c mass, fuel burn and total energy was analysed. Both near future (2020+) and far future (2040+) technology scenarios were applied. Fuel and energy savings up to 11% and 7% respectively were found with the 2020+ scenario. The 2040+ scenario gives respective fuel and energy savings up to 16% and 12%. The savings are mainly caused by reducing the engine core diameter and by the synergies of HEP, MEA and electric taxiing. FC and PV as applied here have almost no effect. With respect to engine downscaling it is remarked that maximally allowed values for HPT inlet temperature may limit the level of downscaling. Furthermore, HEP installation issues such as space, complexity, thermal effects and maintenance aspects, as well as costs were out of scope in this study. These items are envisaged for further research.

## ACKNOWLEDGEMENT

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## NOMENCLATURE

| | |
|---|---|
| $C_L$ | aerodynamic lift coefficient |
| $C_D$ | aerodynamic drag coefficient |
| $C_{L_0}$ | lift coefficient at zero angle of attack |
| $C_{D_0}$ | zero-lift drag coefficient |
| $\Delta C_{D_{flaps}}$ | drag coefficient term dependent on flaps |
| $\Delta C_{D_{gear}}$ | drag coefficient term dependent on gear |
| $\Delta C_{D_{mach}}$ | drag coefficient term dependent on Mach |
| $D$ | aerodynamic drag force, N |
| $D_{ground}$ | ground drag force (rolling friction), N |
| $g$ | gravity constant, m/s$^2$ |

| | |
|---|---|
| $h$ | altitude, m |
| $\dot{h}$ | vertical speed, m/s |
| $k$ | lift induced drag coefficient. |
| $L$ | aerodynamic lift force, N |
| $m$ | aircraft mass, kg |
| $N$ | normal force, N |
| $P_{EM}$ | power supplied by electric motor, W |
| $P_{tot}$ | total engine shaft power, W |
| $PS$ | power split |
| $S_w$ | total wing area, $m^2$ |
| $v$ | true air speed, m/s |
| $\dot{v}$ | acceleration (in flight direction), m/s |

## Greek symbols

| | |
|---|---|
| $\gamma$ | flight path angle, rad |
| $\dot{\gamma}$ | flight path angle rate, rad/s |
| $\mu$ | ground rolling friction coefficient |
| $\rho$ | air density, $kg/m^3$ |

## Subscripts

| | |
|---|---|
| $D$ | drag |
| $D_0$ | zero lift drag |
| $L$ | lift |
| $L_0$ | zero lift |
| $EM$ | electric motor |
| *flaps* | flaps angle |
| *gear* | landing gear setting (up/down) |
| *ground* | ground (rolling friction) |
| *mach* | Mach number |
| *tot* | total (engine shaft power) |
| *w* | wing (total wing area) |

## REFERENCES

Airbus, 2018, Global market forecast 2018-2037.

Airbus Customer Services, 2002, Getting to Grips with Aircraft Performance.

A.W.X. Ang, A. Gangoli Rao, A. Kanakis and W.F. Lammen, 2018, Performance analysis of an electrically assisted propulsion system for a short-range civil aircraft, *Journal of Aerospace Engineering*, 233-4 : 1490-1502, Feb 2018, NLR-TP-2018-019.

B.J. Brelje and J.R. R.A. Martins. 2018, Electric, Hybrid, and Turboelectric Fixed-Wing Aircraft: A Review of Concepts, Models, and Design Approaches, *Progress in Aerospace Sciences,* doi:10.1016/j.paerosci.2018.06.004.

I. Chakraborty, D. N. Mavris and M. Emeneth, 2015, Methodology for Vehicle and Mission Level Comparison of More Electric Aircraft Subsystem Solutions - Application to the Flight Control Actuation System, *Journal of Aerospace Engineering*, 229: 1088-1102.

I. Chakraborty, D. N. Mavris, M. Emeneth, and A. Schneegans, 2016, An Integrated Approach to Vehicle and Subsystem Sizing and Analysis for Novel Subsystem Architectures, *Journal of Aerospace Engineering*, 230: 496–514.

European Aviation Safety Agency (EASA), 2018, Type-Certificate Data Sheet No. EASA.A.064: Airbus A318 - A319 - A320 - A321.

European Union Clean Sky 2 (EU CS2), Large Passenger Aircraft (LPA), URL: https://www.cleansky.eu/large-passenger-aircraft, visited on 9 April 2019.

Gas turbine Simulation Program (GSP), 2019, https://www.gspteam.com, visited on 9 April 2019.

International Civil Aviation Organization (ICAO), 2010, Annex 6 Operation of Aircraft – Part 1: International Commercial Air Transport – Aeroplanes.

National Academies of Sciences (NAS), Engineering, and Medicine, 2016, *Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions,* The National Academies Press, doi:10.17226/23490.

D. Scholz, R. Seresinhe, I. Staack, C. Lawson, 2013, Fuel Consumption due to Shaft Power Off-Takes from the Engine, 4th International Workshop on Aircraft System Technologies, AST 2013.

S.C. Tan, 2018, Electrically Assisted Propulsion & Power Systems for Short-Range Missions: Electrification of a Conventional Airbus A320neo*,* MSc. Thesis TU Delft, April 2018, NLR-TR-2018-153.

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