

Energy Harvesting Frictionless Brakes for Short-Haul Aircraft: Thermal and Electromagnetic Feasibility of an Axial-Flux Machine for a Landing Gear Drive System

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The aviation industry is currently responding to climate change with, among other technologies, electrification of aircraft, and the corresponding onboard electrical architecture provides an opportunity for electromagnetic brakes. The present work introduces a multistage yokeless and segmented armature (YASA) electric machine that replaces friction brakes and harvests kinetic energy throughout a landing. The study establishes the optimal trade-off between weight and electromagnetic torque and translates it into the design requirements for the development of an electric machine. Electromagnetic modeling is conducted using a quasi-3D transient approach and static 3D validation. The results reach 120 Nm/kg active material torque density at approximately 50 A/mm² root mean square current density. The proposed solution enables fitting an electric machine that decelerates an aircraft at autobrake level LOW for Airbus and the "1" and "2" settings for Boeing. A thermal analysis follows, where a novel cruise altitude cooling method is proposed.

I. Introduction

The aerospace industry is growing unprecedentedly, and the projected number of civilian aircraft is expected to double by 2040 compared to 2020, raising many concerns about sustainability [1]. Professional bodies are taking action to reduce the environmental footprint of aviation, and for instance, the Flightpath 2050 vision proposed by European Union Aviation Safety Agency [2] requires emissions-free ground movement.

Both runway-fitted and onboard systems have been introduced to meet Flightpath's objective, including Taxibots at Schiphol and the WheelTug system [3]. Electric taxiing concepts are mature, and once every few years, the subject of electric taxiing receives attention when a new project is released. Nevertheless, none of the undertakings to date has revolutionized the ground movement of aircraft. This indicates that the advantages brought with this novel system have been rather shallow when compared with development and implementation costs. Therefore, a greater impact is needed to draw more attention from regulatory bodies and investors.

Onboard electric taxiing systems so far have been powered by an auxiliary power unit (APU), which generally consumes less fuel than idling main engines throughout the ground movement of the aircraft. However, the APU has limited peak electric power output, and any electric taxiing system that enables high acceleration requires a bespoke APU, which ramps up the cost. An increasing number of electrified systems, such as an electric environment control or

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ice protection system, stretch out the electric architecture of the aircraft, and accordingly, high-power supply, wiring, and storage are being implemented as a part of an more electric aircraft (MEA). A Boeing 787 Dreamliner, taken as an example, has a total electric power output equal to 1.45 MW [4]. An MEA gives an opportunity to look at taxiing systems from a new angle, and accordingly, researchers have investigated energy recovery throughout taxiing, hydrogen fuel cell power supply exclusively for electric taxiing, and battery-powered alternatives [5].

An energy storage present onboard is a distinct opportunity to further extend the functionality of electric taxiing systems to electromagnetic, regenerative braking that would effectively replace friction braking throughout the daily operation of the aircraft. Modern aircraft use carbon-carbon brakes that have an outstanding weight parameter, which comes at the price of energy-intensive manufacturing [6]. The substitution would considerably reduce overhaul costs of landing gear components because electric machines offer longevity in contrast to friction brakes. Finally, the driven-wheels that are continuously coupled to power components would enable wheels pre-spinning prior to touchdown [7]. Thanks to high electric power output in motoring mode, they would aid in takeoff, which would lead to further fuel savings. Each advantage can be achieved with high power and torque electric machines. Nevertheless, aerospace applications are weight and safety critical, and it is crucial to assess whether a torque and power to weight ratio of an electric machine would enable net savings in fuel and consequently, emissions.

The present work investigates the electromagnetic and thermal feasibility of implementing electromagnetic braking in a single-aisle short-haul aircraft. The scientific contribution is as follows: (1) Definition of design constraints and impact on the operations of the aircraft, (2) Electromagnetic and thermal modeling and optimization of high torque density, multistage, axial-flux electric machine integrated into a landing gear drive system, and (3) a novel cooling approach for the proposed electric machine.

II. Application constraints and drive cycle

Maximizing energy efficiency of aircraft is a top priority for each aircraft manufacturer, resulting in an increasing number of systems being present onboard. However, higher complexity also equates to more failure points, which could compromise safety in modern aviation. To ensure safety, well thought out procedures are implemented to minimize the risk of hazardous situations and involve redundancy that mitigates catastrophic incidents caused by single points of failure. These procedures also influence the landing of an aircraft, which commonly relies on the autobrake system to reduce the workload exerted on pilots and minimize the wear rate of landing gear components.

The autobrake system is a closed-loop control circuit that utilizes deceleration feedback from a flight computer unit and compares it with a predefined value. Depending on multiple factors listed in Table 1, the flight computer calculates an optimum autobrake setting. These values are then used in a dynamic model [8] to estimate the corresponding power and torque throughout landing.

Table 1 Reference distances from quick references handbook for both, an A320 [9] and B737-800 [10].

REF DIST (m)										
Autobrake		for 66T		WEIGHT corr		ALT corr	WIND corr	TEMP corr	SLOPE corr	REV corr
A320's			per 1T below	per 1T above	per 1000ft		per 10\deg C			per thrust
			66T	66 T	AMSL	per 5kt TW	above ISA	per 1% downslope		reverser
Operational Landing										operative
Distances (OLDs),	MED	1470	-20	+30	+80	+160	+40	+30		-40
Configuration full	LOW	1970	-20	+40	+90	+180	-60	-30		-10
B737's Normal										
Configuration					per 1000ft			per 1%		
Landing			per 5T	per 5T	AMSL	per 10kt	per 10\deg			one rev/
Distances			below 60T	above 60T	(up to	HW/ TW	above/ below	downslope/		no rev
Flaps 40					8000ft)			upslope		
Dry runway	2	1912	-134	+140	+55	-90 / +315	+50/-49	+29/-26		+35/+35
	1	2115	-160	+166	+65	-104 / +370	+61/-59	+59/-50		+155/+206
Medium reported										
braking action	2	2254	-160	+167	+64	-114/ +408	+58/62	+57/-51		+87/ +213

The reference distances for both Airbus and Boeing include distance from fifteen meters above threshold (300 m of air distance). In the textbook conditions the landing distances can be contained within two km and it is improbable that landing distance will exceed 2.5 km throughout standard operation. The values increase dramatically if reduced braking action is reported and it corresponds to limited tractive effort capability between a runway and aircraft tyres. Theoretically, if autobrake is set and skidding is absent, the actual landing values should remain constant regardless of runway condition. In practice, it is safety critical to increase a safety margin if risk of skidding occurs to avoid runway excursion. Finally, a runway condition may change along its whole distance and pilots may decide to set up a higher autobrake setting to further increase the safe envelope. Figure 1 (a) and (b) show the autobrake interface unit for Airbus and Boeing accordingly. The setting from Airbus tends to have a higher deceleration rate where LOW setting equals to $2.0 \frac{m}{s^2}$ ($1.7 \frac{m}{s^2}$ before) and MED equals to $3.0 \frac{m}{s^2}$ deceleration rate. Boeing comprise one extra step while the lower levels rates tend to be very low where "1" and "2" equates to 1.2 and $1.5 \frac{m}{s^2}$ respectively.

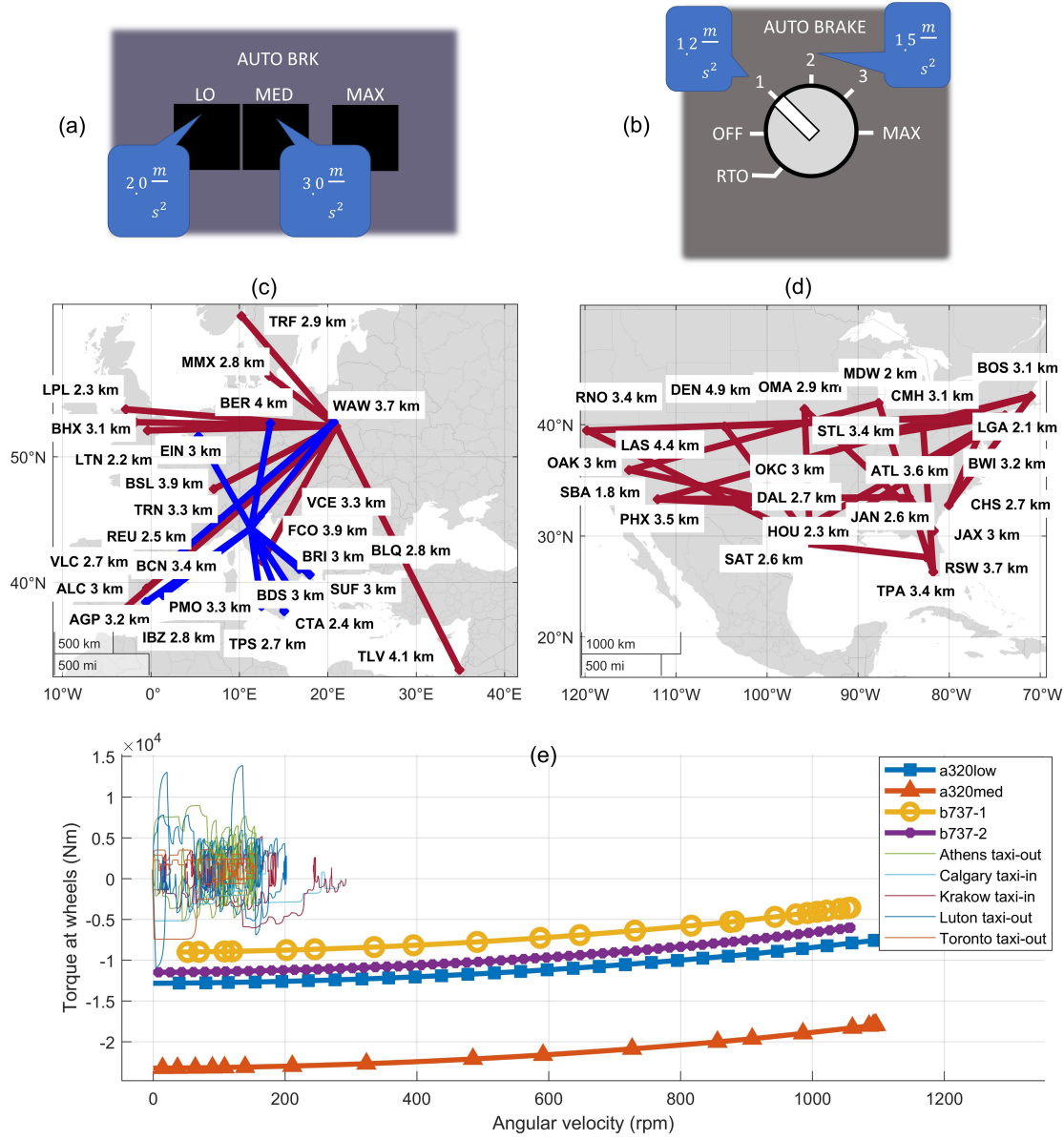


Fig. 1 Design requirements formulation for electric machine: Airbus (a) and Boeing (b) autobrake panels together with given deceleration rates, (c) example runway lengths in Europe, (d) example runway lengths in the US and (e) drive cycles for both landing and taxiing.

Once knowing the deceleration rates and OLDs, it is important to benchmark it with available runway lengths. This was assessed for the three greatest air transportation markets; European countries in Figure 1(c), the US in Figure 1(d) and China. We investigated only short-haul operations with occasional mid-haul flights over the period of seven consecutive days: (1) N8619F; B738, (2) HALXD; A321, (3) 9HQDT; B737-8, (4) B2945; B737-3 and (5) B1318; B738. These aircraft had flown to seventy-two different destinations of which only 3% had runway lengths lesser than 2.1 km and length for 8% was smaller than 2.4 km. The shortest airports often have a larger one in proximity and this is the case for Chicago MDW, New York LGA, London LTN and Liverpool LPL. Therefore, airlines would have an opportunity to alter destinations if the landing gear drive system is present. Such an alteration would incur costs to

airlines however, it may be offset by regulatory bodies which would prioritize airlines that decided to implement the landing gear drive system during, for example, airport slot allocation.

The majority of flights can be executed with lower autobrake settings, we used a dynamic model for the landing gear drive system to estimate torque against speed [8]. Figure 1 (e) shows the resultant drive cycles for both landing and taxiing. An electric machine is subjected to fractional load during the latter in comparison to landing and therefore, optimization takes place to ensure that intermittent high power can be dissipated in generating mode because it is a much greater challenge.

An electric machine in the proposed application is subjected to an unconventional duty cycle. A cycle starts throughout taxiing-out and takeoff where the electric machine uses a fraction of peak performance to propel an aircraft during ground movement. When an aircraft is airborne, the power device is cooled to cruise altitude temperature to maximize its electromagnetic performance. Then, peak performance is exerted throughout the landing to safely decelerate an aircraft. We also consider cooling the machine prior to its usage because it will provide considerable thermal capacity throughout a deceleration cycle. Furthermore, a winding resistance will be reduced leading to smaller Joule heating and an improved B-H curve (second quadrant) of the permanent magnet (PM).

A. Electric machine and design requirements

The capability to replace friction brakes throughout the standard operation of an aircraft allows a saving of as much as eight million dollars corresponding to brake overhaul throughout the life cycle of aircraft. Simultaneously, an electric machine will undoubtedly be heavier than highly optimized carbon-carbon brake units that weigh as little as 40 kg in short-haul aircraft [11]. There is an emphasis on reducing the weight penalty of the proposed solution and therefore, only the highest performance materials are being considered during the development of an electric machine. Unlike in other applications, the materials are unconstrained by budget and consequently, we consider high-grade, N50H [12], NdFeB PMs and Fe-Co Vacoflux 48 lamination steel [13] for this application. The chosen PM grade offers outstanding magnetic flux density and coercivity while remaining working temperature up to 100 °C; any higher grade is limited to 80 °C. Similarly, the cobalt-iron soft-magnetic materials are known for superior hysteresis performance, permeability reaching eighteen thousand and the saturation flux density of 2.3 T. Due to the requirement of present superconducting materials for cryocooling, only copper is considered for winding. However, there is much novelty in manufacturing processes and additive manufacturing can result in maximizing the fill factor. Finally, a material selection for the housing is linked to titanium and aluminium alloys. While titanium is generally better with its yield strength against weight metric, aluminium offers superior thermal conductivity which allows it to timely extract heat. This is especially important for high-current density applications and corresponding conduction between housing and windings. Each of the described materials ramps up the initial costs of the concept nonetheless, the longevity of electric machines will ultimately lead to remarkable savings by the end of the aircraft life cycle.

Besides material selection, the arrangement of PMs known as a Halbach array allows superior power and torque density to be achieved by removing the back iron [14]. Instead, the magnetic flux path is concentrated on one side of the array and runs through a continuous layer of PMs. These advantages are accrued at a price of considerably increased assembly complexity especially when high-strength magnets are used. They have to be assembled in proximity to each other while inducing high repelling forces. There is also an increased risk of demagnetization which can be mitigated by adding a small spacing between magnets.

Finally, a topology for the electric machine is selected to be a YASA primarily because it would be relatively easy to integrate inside the wheel and reuse the keys of a wheel rim. Secondly, this topology is known due to its geometry which further maximizes torque density of the proposed machine. Figure 2 shows the electric machine for the landing gear drive system demonstrator.

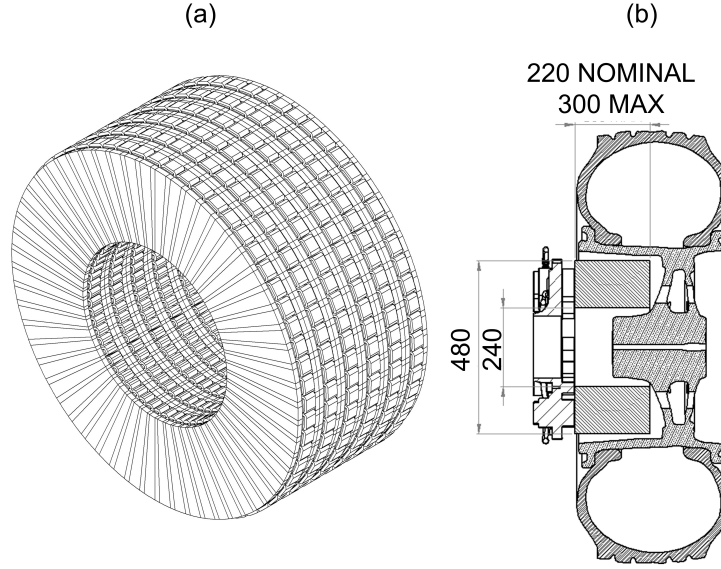


Fig. 2 Electric machine for the landing gear drive system; (a) demonstrator of assembled electric machine, (b) volumetric constraints associated with a short-haul aircraft landing gear.

As can be seen in Fig 2 (a), six stacks are used to match the torque constraints. Nevertheless, the stacking capability is limited by axial length as can be seen in Figure 2 (b) which shows the volumetric design space [15]. This is met by using a high aspect ratio of outer diameter to axial length equal to as much as ten. Electric machines can operate in motoring, generating and braking modes. For a PM synchronous machine, both motoring and braking rely on external excitation whereas, for generating mode, the PMs are the source of excitation. The amount of electromotive force (EMF) is proportional to the angular velocity of a machine and it is impractical to harvest kinetic energy at very low angular speeds due to the voltage difference between an energy storage and an electric machine.

To ensure that an electric machine can seamlessly operate in the low angular speed regions, we consider high pole-segment combinations reaching up to 58 poles and 60 segments. The higher count leads to a higher ratio between mechanical and electrical revolution and consequently, sufficient EMF for generating mode can be achieved with more ease at lower speeds throughout landing deceleration. Otherwise, the electric machine can decelerate an aircraft by braking (also known as plugging) which is similar to motoring mode, but phase offset equals 180 degree. The major drawback of plugging is the prohibitive amount of heat. In these circumstances, the remaining kinetic energy of an aircraft would be converted to heat inside an electric machine and therefore, it can only be applied at the end of landing deceleration in near standstill conditions.

Knowing that the device will be safety critical, we assume that the magnetic flux path is independent for each segment and in addition, we increased the number of phases up to seven phases separated by stacks. If at any point a winding failure occurs in such a seven-phase, six-stack machine, the braking performance would be reduced by only 0.6% which would have a negligible impact on safe operation.

III. Electromagnetic design and optimization of yokeless axial-flux machine

The development of an electric machine for a landing cycle is a much greater engineering challenge than a drive for electric taxiing. Therefore, electromagnetic optimization takes place based on the drive cycle for the multiple autobrake settings. Figure 3 presents the genetic optimization algorithm used in the process. The design constraints were defined according to the assumptions given in the previous sections. Accordingly, we estimate that the feasibility point can be

described as torque demand t_{dem} equal 12 kNm, power demand P_{dem} equal 0.96 MW. The angular speed of the cycle in standard operation ω_{dem} is limited to approximately 1200 RPM however, the electric machine must remain intact in case of an overspeed landing. Aircraft tyre certification is used as a reference and accordingly, maximum speed equates to approximately 2000 RPM. The outer r_o and inner radii are derived from preliminary design equations for a landing gear [11] and correspond to 240 and 120 mm respectively. Finally, the maximum mass m_{max} is not fixed because it is heavily dependent on aircraft operation and an electric machine weighing 300 kg would still be beneficial for aircraft which execute only short-haul flights. Nevertheless, we set the target of 160 kg maximum weight to ensure that the landing gear drive system remains applicable to a broad range of applications.

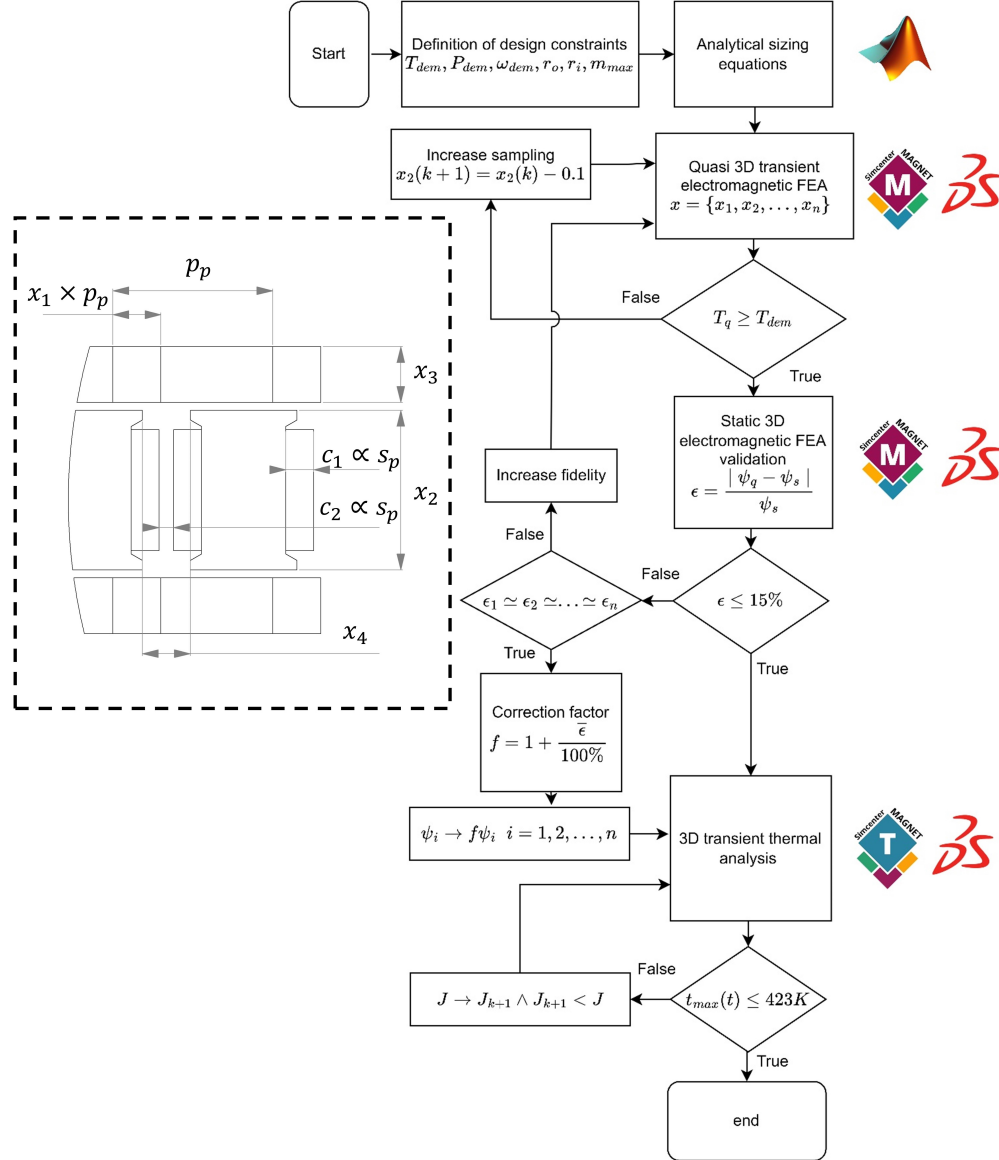


Fig. 3 Optimization algorithm for the present work, including the optimization objectives, variables, validation and correction factor.

Having the design constraints defined allows us to progress into analytical modelling which relies on the following sizing equation for power output [16]:

$$P_{out} = \frac{m}{m_1} \pi^2 \frac{(1+k_d)(1-k_d^2)}{8} k_{w1} n_s B_g A_s \eta \cos\phi D_o^3 \frac{V_1}{E_f} \quad (1)$$

where the value of m represents the number of phases, m_1 denotes the number of phases for each stator, In case there are multiple stators, it can be assumed that each stator has an identical value of m_1 (i.e., the number of phases for each stator remains constant). k_d is the aspect ratio of outer diameter to axial length, k_{w1} is the fundamental winding factor, D_o is the outer diameter, n_s is the rotational speed in rev/s, B_g is the air gap flux density, A_s is the specific electric loading, η is the efficiency and $\cos\phi$ is the generator power factor.

The PM thickness is calculated as:

$$l_{pm} = \frac{\frac{2K_r}{2+K_{rm}} \mu_r B_g g}{k_l B_r - B_g / C_\phi} \quad (2)$$

where k_r is the reluctance factor of the steel path, which is typically in the range of $1 < k_r \leq 1.2$, k_{rm} is the reluctance factor to accommodate/ consider the reluctance of tangential arrangement of Halbach magnet, μ_r is the recoil permeability, g is the air gap, k_l is the leakage factor which is typically less than one, B_r is the residual flux density of PMs and C_ϕ is the PM concentration factor.

The length of segments is derived from:

$$l_s = \frac{I \pi D_o (1+k_d)}{2\sqrt{2} N_t k_{w1} J_{rms} k_f} \quad (3)$$

where I is the specific electrical loading, N_t is the number of turns, J_{rms} is the root mean square (rms) value of current density and k_f is the slot fill factor.

The analytical equations led to preliminary variable dimensions however, the finite element analysis was conducted for multiple variables to investigate the influence of the nonlinear magnetic performance of the components. Figure 4 (a) shows the magnetic flux density for the quasi 3D model and that the knee point which induces nonlinearity from approximately 1.8 T onwards is reached. This phenomenon is further visible in Figure 4 (b) which indicates that the saturation phenomenon is more severe at lower radii. In a motoring mode, exceeding the knee point is highly undesired because exponentially more current must be passed through the coils to achieve a torque increase while the ohmic losses are proportional to the square of the current. In the generating mode, having the flux density in proximity to the knee point region indicates that there is a balance between the amounts of PMs and the core materials.

The geometry was optimized numerically according to the Halbach array proportion of axially-facing to side-facing components x_1 , the segment axial length (x_2), the PM axial length (x_3), the arc of the segment (x_4). Furthermore, we investigated the influence of the varying number of segments and poles. Accordingly, we scaled the winding (c_1) and the housing (c_2) thicknesses proportionally to a number of segments.

The FEA assumptions were set and the tight stacking of multiple YASA machines together with the Halbach array arrangement of PMs have another distinctive advantage. The multiple stacks are arranged so the PMs located at the rotors of each stack tend to repel each other and thus, concentrate the magnetic flux on the stator sides with reduced leakage. We captured this phenomenon by neglecting the flux leakage in axial direction. However, the flux can still exit the machine in the radial direction and accordingly, in the full 3D model, the outer diameter of the airbox is 100 mm greater than the outer diameter of the geometry. These assumptions allowed us to manipulate the proportion of side- and axial-facing segments without concerns about flux concentration as shown in Figure 4. The best results were achieved for the generator when the ratio of axial-facing to the side-facing PM arc lengths is equal to 0.3 but this approach has to be validated for coil excitation in motoring mode.

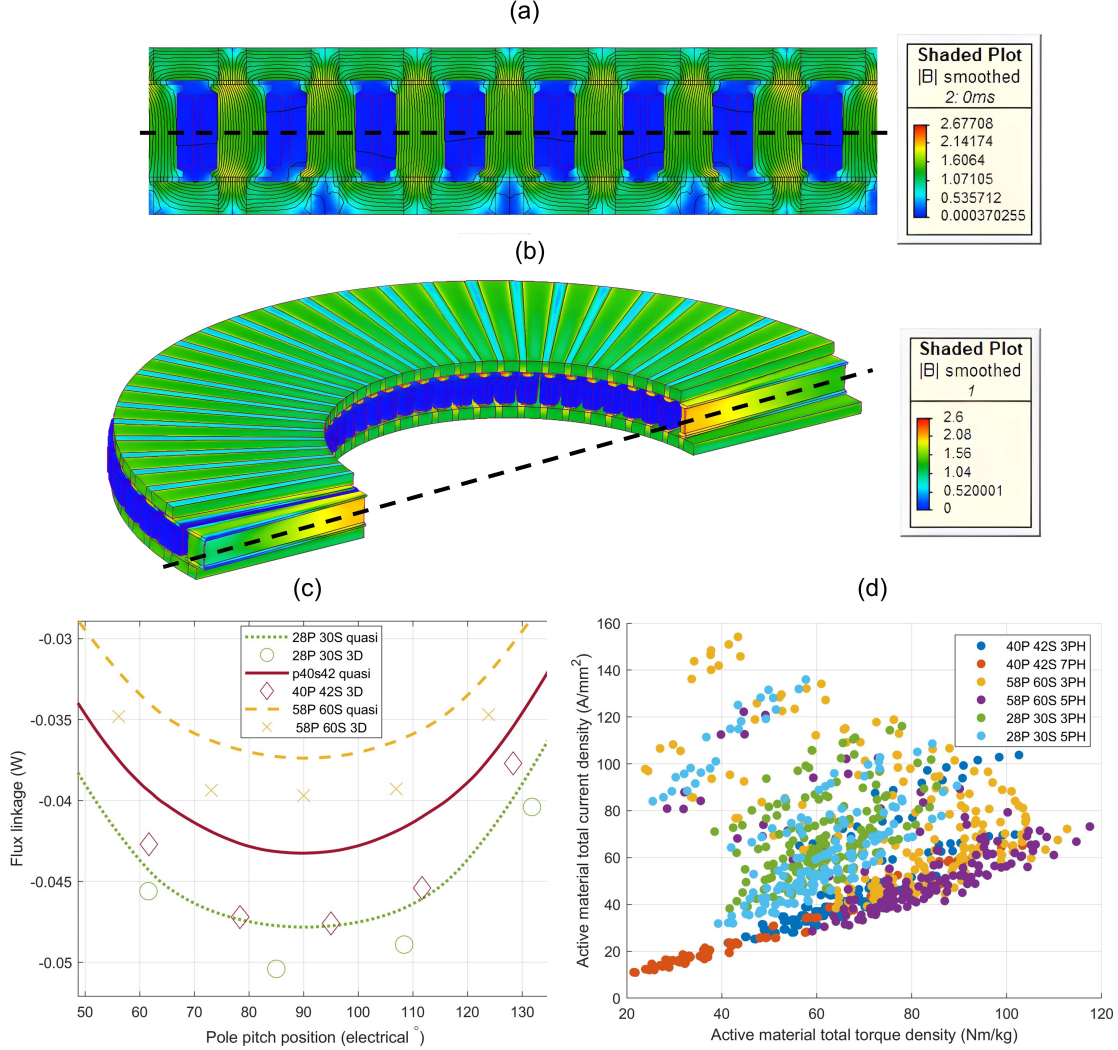


Fig. 4 Electromagnetic FEA for the proposed electric machine: (a) quasi 3D and (b) 3D model magnetic flux paths and distribution of flux density; intermittent lines indicate the symmetry planes, (c) validation according to flux linkage, (d) Performance benchmark of all iterations showing the peak current density against the torque density.

The quasi 3D approach allowed us to minimize computing time to obtain the results however, this approach neglects the end effects at both radial ends of the machine. We also sliced the model for selected iterations and the intermittent black line in both Figure 4 (a) and (b) illustrate these planes. To ensure the accuracy of results, we validated (see Fig. 4 (c)) the quasi 3D data with high-fidelity static 3D FEA by comparing the flux linkage at different electrical angles. The comparison reveal a small error after the peak value convergence check: $\epsilon_{60s} = 6.2\%$, $\epsilon_{42s} = 9.1\%$ and $\epsilon_{30s} = 5.1\%$. Unusually, the peak values from 3D results were higher in each case. The most probable reason for this occurrence is the limited number of slices in quasi 3D analyses.

The simulation was conducted for nearly 600 different geometry and load setups. The iterative process for both Quasi-3D and 3D FEA was automated; the geometries were created in SolidWorks, which were later imported into Simcenter Magnet and solved. Then, the FEA data were fed into MATLAB and cleaned for analysis (Raw data available

in Data Availability Statement). Figure 4 (d) shows a performance benchmark of active material total torque density against the root mean square current density. As expected, the higher number of poles and segments led to increased torque density. The flux saturation nonlinearity can be observed by assessing the best-case iterations.

The transient results of magnetic flux change are presented in Figure 5 where nine steps across a whole pole pitch were taken into account. The machine was halved in axial direction according to the symmetry plane of magnetic path minimizing the computational cost of each simulation.

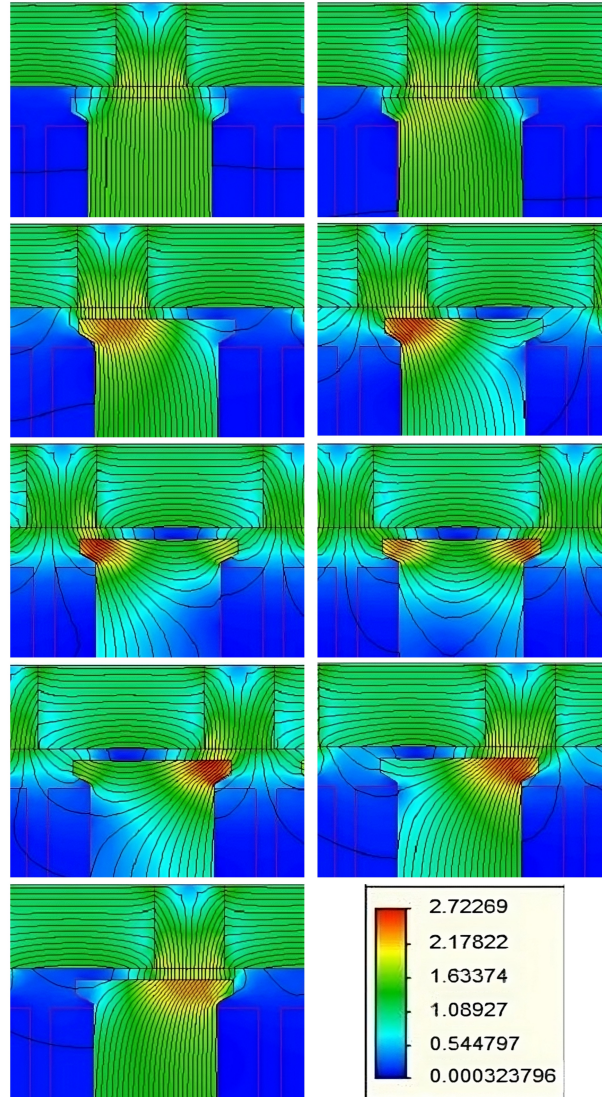


Fig. 5 Magnetic flux density for nine steps of quasi 3D transient simulation at 1000 rpm.

The change in flux density throughout a single pole pitch indicates that saturation is achieved at the stator tooth however, increasing its size leads to reduced performance due to increased flux leakage. In the worst case scenarios, when the axially-facing PMs and the stator teeth were large enough, the magnetic flux path circulated through a single rotor without penetrating through the core.

IV. Thermal considerations

High performance machines generate a large amount of heat and thermal analysis must be executed to provide answers regarding the feasibility of an electric machine for the landing gear drive system. This cycle differs from a standard automotive application due to its intermittent nature, and an electric machine is cooled prior to peak power application and has a considerable thermal capacity up to an overheating point. Contrary to internal combustion engines which require working temperature for safe operation, electric machines take advantage of low temperatures due to increased coercivity and higher flux density of PMs and reduced resistivity of copper.

A cruise altitude opens the possibility of further cooling down the electric machine prior to touchdown. This is applicable even to short-haul flights executed by A320s and B737s. Figure 6 (a) shows three flights in Europe that are shorter than one hour and in each case an aircraft reached an altitude that corresponds to International Standard Atmosphere's (ISA) temperature lower or equal to minus forty degrees Celsius. Utilizing this temperature by, for example, taking a small amount of air from NACA ducts would allow cooling the electric machines to as low as minus thirty degrees Celsius upon touchdown. As an outcome, the reduced Ohmic losses and increased electromagnetic performance would lead to even higher torque density throughout a landing.

Since the proposed method for the electric machine pre-cycle cooling requires more research regarding the concept feasibility, we used the conservative initial temperature of minus twenty degree Celsius in our semi-analytical model. Figure 6 (b) illustrates that the single segment was taken out of the inner stack because the highest temperature rise is expected in the middle of the motor and the assumption was made that an equal amount of heat is generated in each segment and pole of this multistage electric machine. Consequently, we made an approximation that there are two symmetry planes (perfect insulators) in the axial direction flush to the PM outer faces and two additional symmetry planes equally spaced between two segments. The aluminium stator housing and the retaining sleeve components were added respectively to symmetry planes to increase the amount of heatsink material. Knowing that the landing cycle ends within thirty seconds, we assumed that the system is adiabatic.

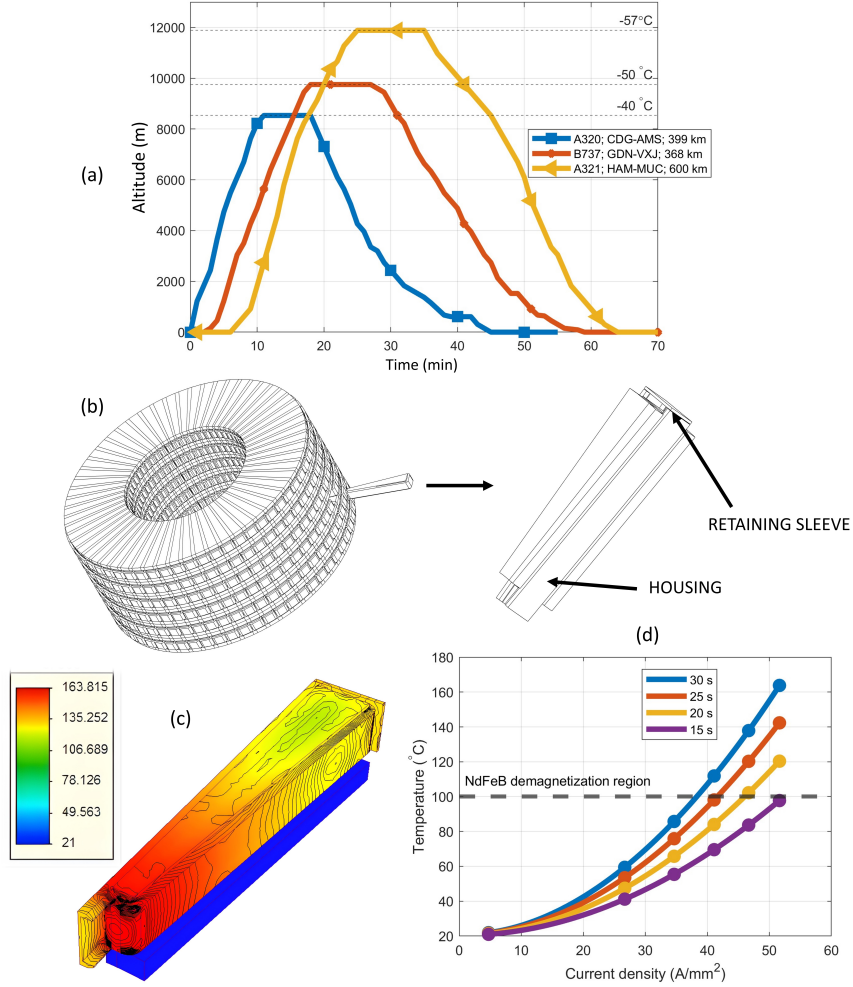


Fig. 6 Thermal modelling of the electric machine: (a) Example short-haul flights that potentially permit cruise altitude cooling, (b) thermal simulation geometry initialization, (c) temperature shaded results for the highest current density simulated in Simcenter MAGNET Thermal, (d) Plot of temperature of winding against the current density at 15s, 20s, 25s, and 30s.

High torque and power density metrics require high current density which is an indication of high Joule losses which will be markedly higher than eddy currents, hysteresis and mechanical factors. The simulation reflects eddy current losses in the PMs and the stator core equal 2 and 0.9 W respectively. They were sourced from the quasi 3D electromagnetic FEA. The hysteresis losses equal 2.6 W were applied in a similar manner. Finally, the ohmic losses were hand calculated because the quasi 3D approach skips the end windings. First, the mean length of winding was measured in the CAD software and then, the heat loss was calculated:

$$H(t) = I^2 \frac{\rho_r(t) l_{ws}}{\frac{\sigma_s}{N_t} \rho_c} \quad (4)$$

where I is the phase current density, ρ_r is the resistivity of copper, l_{ws} is the winding length per winding per segment, σ_s is the total winding cross section, N_t is the number of turns and ρ_c is the copper fill factor.

The simulation was conducted for different current densities up to 52 $\frac{A}{mm^2}$ and Figure 6 (c) shows the transient

results for the worst case scenario after the heating. The upper layer of PMs and a single side of housing were included in the simulation but removed from the figure to increase clarity. The highest recorded temperature equals 163 degree Celsius and as anticipated, the hot spot is present at the inner radius of the electric machine because the ratio of heat source to heatsink material decreases with the radius. The heat transfer between the core and the PMs was minimal due to a short period. Figure 6 (d) shows the plot of winding maximum temperature against the RMS current density after 15, 20, 25 and 30 s. The highlighted NdFeB demagnetization border indicates that the higher current densities will heat the winding and the core to temperatures exceeding the maximum safe temperature of the PMs above which they will demagnetize. While it is safe for the period of landing due to limited heat transfer through the airgap, the heat will be transferred at a later stage and may lead to irreversible demagnetization. The best possible mitigation is the cooling that allows controlling the temperature of the PMs after the landing. Besides the PMs temperature limitation, the winding material, iron core and housing can easily withstand the simulated temperatures. The insulation temperature rating is the primary limitation for these materials however, there are commercially available materials that sustain up to 400 degree Celsius. This simulation demonstrates that there is enough thermal capacity to sustain high current densities occurring during the landing. However, the results are limited regarding the heat transfer and neglect the heat transfer resistivity of insulation varnish.

V. Conclusions

The present work demonstrated the electromagnetic and thermal feasibility of the high power YASA machines used for regenerative braking during the landing of a short-haul aircraft. The proposed application was reviewed together with the impact of the proposed solution on the operations of aircraft. The optimum trade-off between weight and electromagnetic torque was established and later translated to the design requirements typical for the development of electric machines. Then, the electromagnetic modelling took place where the quasi 3D transient analysis of YASA topology was used for multi-objective, electromagnetic optimization. The results were validated with a high fidelity static 3D model and the flux linkages of both were compared. It was demonstrated that the proposed solution achieves $120 \frac{\text{Nm}}{\text{kg}}$ active material torque density at approximately $50 \frac{\text{A}}{\text{mm}^2}$ current density. This amount allows fitting an electric machine that will decelerate an aircraft at autobrake level LOW for Airbus and 1 and 2 for Boeing. After the electromagnetic development, the thermal analysis was considered where the novel cruise altitude cooling method for the electric machine was proposed. The thermal analysis demonstrated that the current densities up to $40 \frac{\text{A}}{\text{mm}^2}$ allow operating without liquid cooling while higher current values would permit the safe deceleration of an aircraft but the PMs would overheat after the landing.

The functionality of high-performance electric machines can be extended into the landing gear drive system. Therefore, allowing the machines to be used throughout taxiing and to aid a takeoff. This approach would maximize the expected fuel savings resulting in a corresponding reduction in greenhouse gases. Finally, the energy harvested throughout landing can be reused throughout taxiing in, and if combined with energy storage with a size similar to an electric car battery, the proposed electric machine further extends the applicability of the landing gear drive system. The future work will focus on higher fidelity electromagnetic and thermal development and wide-context integration of the landing gear drive system into the architecture of an MEA.

VI. Data availability statement

The data that support the findings of this study are openly available in Cranfield Online Research Data (CORD) at <https://doi.org/10.17862/cranfield.rd.22814771>

VII. Acknowledgments

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References

- [1] Shparberg, S., and Lange, B., “Global Market Forecast 2022,” Tech. rep., Airbus, Toulouse, 2022.
- [2] European Union Aviation Safety Agency, *European aviation environmental : report 2019*, Publications Office, 2019. <https://doi.org/doi/10.2822/309946>.
- [3] Lukic, M., Giangrande, P., Hebala, A., Nuzzo, S., and Galea, M., “Review, Challenges, and Future Developments of Electric Taxiing Systems,” *IEEE Transactions on Transportation Electrification*, Vol. 5, No. 4, 2019, pp. 1441–1457. <https://doi.org/10.1109/TTE.2019.2956862>, URL <https://ieeexplore.ieee.org/document/8918079/>.
- [4] Buticchi, G., Wheeler, P., and Boroyevich, D., “The More-Electric Aircraft and Beyond,” *Proceedings of the IEEE*, Vol. 111, 2023, pp. 356–370. <https://doi.org/10.1109/JPROC.2022.3152995>.
- [5] Deja, J., Dayyani, I., and Skote, M., “Modeling and performance evaluation of sustainable arresting gear energy recovery system for commercial aircraft,” *International Journal of Green Energy*, 2022, pp. 1–15. <https://doi.org/10.1080/15435075.2022.2143715>, URL <https://doi.org/10.1080/15435075.2022.2143715>, doi: 10.1080/15435075.2022.2143715.
- [6] Gadow, R., and Jiménez, M., “Carbon fiber-reinforced carbon composites for aircraft brakes,” *Am. Ceram. Soc. Bull.*, Vol. 98, No. 6, 2019, pp. 28–34.
- [7] Mahjouri, S., Shabani, R., and Skote, M., “Reducing temperature, drag load and wear during aircraft tyre spin-up,” *Aircraft Engineering and Aerospace Technology*, Vol. 94, 2022, pp. 906–914. <https://doi.org/10.1108/AEAT-09-2021-0287>.
- [8] Deja, J., Dayyani, I., Nair, V., and Skote, M., “More Electric Aircraft Conversion to All-Electric During Ground Operations: Battery Powered Landing Gear Drive System,” *IEEE Transactions on Transportation Electrification*, 2023, pp. 1–1. <https://doi.org/10.1109/TTE.2023.3262208>.
- [9] Kornstaedt, L., and Lignee, R., “Operational Landing Distances, A new standard for in-flight landing distance assessment,” *Safety*, Vol. 10, 2010, pp. 1–5.
- [10] Boeing, “737 Flight Crew Operations Manual,” , 2009.
- [11] Schmidt, R. K., “4.4.3 Weight,” , 2020. URL <https://app.knovel.com/hotlink/khtml/id:kt012NOKU4/design-aircraft-landing/weight>.
- [12] Qiu, S., Zhao, W., Zhang, C., Shek, J. K. H., and Wang, H., “A Novel Structure of Tubular Staggered Transverse-Flux Permanent-Magnet Linear Generator for Wave Energy Conversion,” *IEEE Transactions on Energy Conversion*, Vol. 37, 2022, pp. 24–35. <https://doi.org/10.1109/TEC.2021.3088722>.
- [13] Swanke, J., Bobba, D., Jahns, T., and Sarlioglu, B., “Design of High-Speed Permanent Magnet Machine for Aerospace Propulsion,” American Institute of Aeronautics and Astronautics, 2019. <https://doi.org/10.2514/6.2019-4483>.

- [14] Huang, R., Liu, C., Song, Z., and Zhao, H., “Design and Analysis of a Novel Axial-Radial Flux Permanent Magnet Machine with Halbach-Array Permanent Magnets,” *Energies*, Vol. 14, 2021, p. 3639. <https://doi.org/10.3390/en14123639>.
- [15] Raminosoa, T., Hamiti, T., Galea, M., and Gerada, C., “Feasibility and electromagnetic design of direct drive wheel actuator for green taxiing,” *IEEE*, 2011, pp. 2798–2804. <https://doi.org/10.1109/ECCE.2011.6064145>.
- [16] Gieras, J. F., Wang, R.-J., and Kamper, M. J., *Axial Flux Permanent Magnet Brushless Machines*, Springer Netherlands, 2008. <https://doi.org/10.1007/978-1-4020-8227-6>, URL <http://link.springer.com/10.1007/978-1-4020-8227-6>.



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