Electromagnetic Brake/Drive Unit design for small aircraft environmentally friendly ground operations

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Abstract: This paper introduces a concept to reduce the harmful gaseous emissions of aircraft produced during ground operations. The idea is an integrated solution using a frictionless electromagnetic brake system, which is also capable of operation in drive mode. Using this system, less power is required from the engines during taxi, resulting in potential fuel savings. In this paper a typical business jet was used as an example aircraft to demonstrate the concept. For small aircraft taxi losses can be significant compared to the total mass of the aircraft, however braking power is more manageable than in the case of larger aircraft, airliners for example. After the preliminary simulation of the braking and taxiing phases, system requirements were determined and the system architecture was designed. Particular focus was placed on system safety, reliability, and economic benefits. Besides these primary considerations, novel ideas were also investigated, like the favorable effect of the landing gear spinning up on tire life, or the reduced wear of the break unit.

1. INTRODUCTION

One of the most significant issues near to airports – besides the noise – is the local air quality; which is strongly influenced by the density of the air traffic. Aircraft engines operate by burning hydrocarbon fuels, which results in pollutant emissions. This is particularly concerning on the ground, where the emitted gases stay concentrated close to the airport facilities, and in the airport's environment. Organizations, such as the Clinton Climate Innovative and others have proposed numerous projects and programmes in order to reduce the environmental impact of aircraft. In addition to the ground emissions, aircraft are also continuously improved to meet with increasingly stricter environmental demands, and restrictions.

The major harmful pollutants emitted by aircraft are: Carbon Monoxide (CO), Unburned Hydrocarbons (HC), Nitrogen Oxides (NO_x), Ozone (O_3) and Particulate Matter (PM). The different pollutants have numerous undesirable effects; CO can cause cardiovascular problems, especially for those with existing heart conditions. Also the pollutant prevents damaged cell from regenerating, causing permanent damage. HC can cause dizziness, headaches, visual disorders and memory impairment. NO_x have effect of lung irritation or lower resistance to respiratory infections. O_3 is also harmful to the lung tissues, increase the possibility to respiratory infection. The aggressive PM also damages the lung, and in

addition inhaling excessive amounts leads to premature mortality and aggravation of respiratory and cardiovascular disease, while it also decreases the efficiency of the body's defence mechanism. Ozone and PM furthermore are carcinogenic. There are models to estimate the pollutants in the exhaust gas emissions during ground operations, like it is described by Deonandan and Balakrishnan.

ICAO has set emission limits for aircraft engines in order to reduce the mentioned harmful effects, which must to be met to get type certification. The process of the certification is made up from test bed measurements in 4 different operating modes to simulate accurately the various flight modes. These are take-off, climbing, approach and taxi. That means 4 different thrust power settings for specific period of time, in the following order: 100 % for 0.7 minute (take-off), 85 % for 2.2 minutes (climbing), 30 % for 4 minutes (approach) and 7 % for 26 minutes (taxi). New engines are being developed – like the CFM LEAP engines – that are able to reduce the harmful emissions while also improve engine efficiency.

A new strategy is to completely turn off the main engines of an aircraft during ground operations, and drive using electrical power. This solution has several advantages compared to the all or single engine taxiing strategy. Ithnan, Selderbeek, Beelaers van Blokland, Lodewijks have investigated the problem, and highlighted the main disadvantage; during flight, the electrical drive motor's added

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mass imposes a fuel penalty on the aircraft operation. This paper introduces a novel system, which integrates the advantages of electrical taxiing with the brake system for a small, business jet sized aircraft. This class of aircraft can use up comparably high fraction of its MTOM during extended taxi operations.

Current aircraft brake systems rely exclusively on friction to provide braking torque. The friction brakes are usually assisted with the vehicle's aerodynamic surfaces and in most cases thrust-reversers to alleviate the system, but they are still under heavy loads. Friction brakes are usually actuated with hydraulic power, a power source which is losing more and more ground to the more electric solutions.

In our concept we are proposing a different technology to deliver the braking torque, in the form of an electro-magnetic rotating machine, more specifically an Electromagnetic Brake/Drive Unit (EBDU). Electro-magnetic rotating machines provide braking torque in the form of the Lorentz force, which is generated by the movement of electric charges in a magnetic field. As a result, the system provides a solution to remove friction from the braking process, resulting in many advantages. Electro-magnetic brakes have wide-spread use, such as on light rail vehicles or dyno-pads for engine testing. These machines also provide the possibility to regenerate some part of the energy normally dissipated during braking.

2. SIMULATION OF BRAKING CONDITIONS

The scope of the recent work is to determine the conceptual system properties of an electromagnetic frictionless brake/drive system. The system must provide the same or better performance, system reliability and safety as the current friction-brake systems, while also enabling more advanced possibilities.

To accurately describe the system properties and required components, a typical business jet aircraft has been selected as the concept demonstrator; the Pilatus Aircraft PC-24 model, since the contribution of small aircraft in the air traffic is continuously increasing according to Rohács D. and Rohács J. The specifications of this aircraft were derived using various sources; and all the requirements were defined based on CS 23.

The most challenging part of the concept is to provide break performance and safety at least similar to the current friction brakes. Thus the first step is to simulate the braking conditions.

2.1. Simulation of Braking Conditions

The braking conditions consider two critical scenarios: rejected take-off (RTO) and landing at MLM (assumed to be equivalent to MTOM). The conditions were simulated for both dry and wet runways. Furthermore, two different values of deceleration were assumed; the maximum achievable based on the maximum ground friction coefficient, and a

Certification Specification derived minimum acceleration of 3.1 m/s^2 (landing) or 1.7 m/s^2 (RTO).

Lift and drag coefficients are taken as typical values for a light business jet, methodology and recommendations provided by Howe's and Roskam's aircraft design books. Mass and geometry data is also based on the PC-24. The calculations assume conservative deceleration, as the vehicle is assumed to generate lift all the way through, while the drag coefficient is approximated with the cruise (clean configuration) value; thus the brakes can exert lower maximum forces, and have to work harder, since there is less assistance from aerodynamic drag.

A typical result from the deceleration simulation, the time history of the braking power and torque at MLM conditions on a wet runway, applying maximum available braking power, is shown in Fig 1.
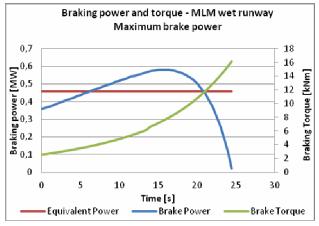

Fig 1. Braking power and torque - MLM wet runway Maximum brake power

The summary of all the different braking cases are shown in Fig 2 and Fig 3, for the maximum possible, and minimum required deceleration respectively.
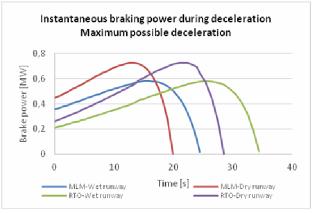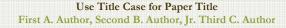

Fig 2. Instantaneous braking power during deceleration Maximum possible deceleration
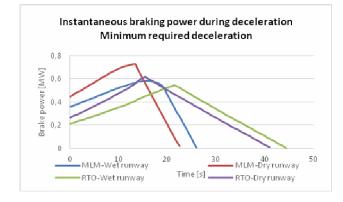
Fig 3. Instantaneous braking power during deceleration Minimum required deceleration

What can be seen from the simulations that the maximum braking power occurs at MLM, dry runway conditions, under maximum deceleration. This maximum power is a predicted 726 kW, which figure forms one half of the electric motor conceptual sizing.

2.2. Electric Machine Review

The heart of the frictionless brake and drive system is the electromagnetic rotating machine capable of providing both braking torque (generator mode) or driving torque (drive or motor mode).

Rotating electric machines have been used for many decades, and thus present a proven and mature technology. They are commonly used in aviation, mainly to generate electric power by taking shaft power from the main propulsion units. Various other secondary applications exist, getting more and more common with the emergence of the more electric aircraft concepts. They can be used to drive compressors for environmental control systems or as electro-hydraulic actuation systems. These secondary applications require relatively low amount of energy compared to a primary system.

In terms of primary power, in recent years there have been many advancements in aviation grade electric motors. Wentz and Myose estimated propulsion electric motor power density. Based on a NASA study, published by Berton, Freeh and Wickenheiser, the current (2003) off-the-shelf technology has an average power density of 1.15 kW/kg, while predicted future technologies have the potential for 2.47 (intermediate technology) to 8.21 kW//kg (advanced superconducting designs). Other prospective studies envision even higher power densities, in the range of 33.4 kW/kg (1 MW power for 66 lb), as it was introduced by Alexander, Lee, Guynn and Bushnell. This advanced concept envisions non-ferrous design along with 20 K operating temperatures.
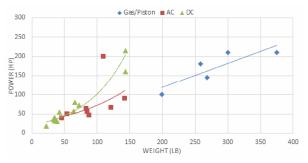

Fig 4. Power line graph for electric and combustion motors

Bari, Roof, Oza and Chudoba published a study, which introduces and compares the different electric and combustion motors from the viewpoint of power-weight relationship. It can be stated, that however electric motors in the required power-requirement range, further developments are needed to optimize the power density ratio of the electrical motors for the exact purpose.

Rotating electric machines are also widely used in other fields, such as marine, light rail, power generation and more and more commonly in motorsports, with some near term applications reaching up to 12 kW/kg power density.

2.3. Energy Storage Review

The rotating electromagnetic machine used to provide braking torque naturally lends itself to implement an energy storage system, regenerating some of the enormous amount of energy that otherwise would have been dissipated as heat. The caveat in this is the fact, that energy storage units, mainly batteries and capacitors in our case, are usually heavy equipment, and a balance has to be found between regenerating energy, and imposing additional weight penalty on the aircraft.

Electric energy as it was mentioned can be most conveniently stored in either batteries or capacitors. Technologies such as fuel cells, or other alternative hydrogen storage technology exist, but they are still mainly specialist equipment, used on specialist vehicles like the Space Shuttle.

Fig 5 shows the Ragone plot, which is the key tool to understand the behaviour of the two different classes of energy storage devices. It shows that batteries can hold high amount of energy, but they can only process it at a lower rate. Capacitors on the other hand, are capable of dealing with short, but intensive power loads. Assuming that a battery and a capacitor can be charged and discharged at the same rate (power), we can narrow down the search space based on our requirements.
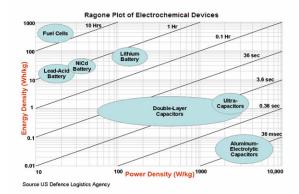
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Fig 5. Ragone plot of electrochemical devices

As we established in previous chapters, the length of a braking event lasts between 20 – 45 seconds, higher values are for refused take-off while landing is generally shorter. The values are calculated assuming that the aircraft is slowed to a complete stop, which is rarely a case during landing. This short duration means that batteries or fuel cells would not be able to cope with the high loads, system damage or more serious events could occur. The devices that promise the best solution would be either the double-layer capacitors or ultra-capacitors (super-capacitors).

2.4. Estimation of Taxiing

The taxi requirements were identified based on the data provided by past research papers, published by Dzikus According to their research, in 2007 aircraft in the United States spent on average around 17 minutes taxiing out and usually below 10 minutes taxiing in. Also they realised that the fuel consumption is mainly dependent on the time spent taxiing, and effects of mass change for example are negligent. Balakrishnan and Hansman found that aircraft in Europe spend about 10-30 percent of their flight time taxiing, and for example a short/medium range A320 could spend up to 10 percent of its fuel on the ground. This ratio is even higher for a business jet. Robinson and Murphy have investigated the time spent taxiing in the United States in 2008, which varies from 37 to 7 percent of flight time (short and long flights respectively) with an average of 23 minutes.

As a result it can be seen, that the power requirement is sized based on the landing conditions, assuming that the machine has the same rating both in brake and drive mode.

3. SYSTEM ARCHITECTURE

The main element of the EBDU system is an electro-magnetic rotating machine. This unit can either function as a brake (generator), or can be run in drive (motor) mode, thus provide more efficient and ecologically desirable form of taxiing. To decide which operation mode is active, an EBDU controller unit is responsible.
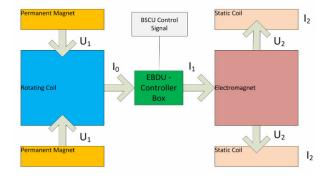

Fig 6. EBDU operation principle

The investigated system is designed to be operated in four different modes:

1. Normal braking/without anti-skid
2. Differential braking with/without anti-skid
3. Emergency/parking braking
4. Drive mode

3.1. Normal Braking

In normal braking mode the landing gear breaks are operated automatically by a controller unit. In a conventional friction brake system, the brakes are regulated by electro-hydraulic valves, controlled by the controller unit. In the proposed system however, no hydraulic power is required, the Electromagnetic Brake/Drive Unit (EBDU) is controlled electronically, and therefore no valves, hydraulic lines, or anti-skid switches are needed, as all these features can be provided by controlling the excitation current of the EBDU. Furthermore the lag in brake control can be also reduced, which for friction systems is in the magnitude of 0.1 sec to milliseconds. Signal from the EBDU could be directly routed to existing anti-skid systems, providing seamless integration to existing systems. Due to the elimination of friction, the disc relative speeds no longer limit the speed at which braking can be started, allowing for potentially higher touchdown speeds.

Brake performance can be further increased by integrating other brake mechanisms, such as speed brakes and thrust reversers. The brake system control unit can send control signals to the engine interface controller unit, or flight controllers to perform integrated braking, reducing the pilot workload during landing. The deceleration provided by the automatic system could be set with pushbutton switches, with an option between LOW, MED or MAX. Manual operation will still be retained, as it is required by airworthiness. This can be done by linking the excitation current directly to pedal travel, while allowing the pilots to disable the brake system control unit. In the event of system failures, normal braking mode is automatically switched to Alternate braking mode.

3.2. Differential braking

Differential braking enables the aircraft to apply different braking force on its wheels, which can be used to stabilize the aircraft, for example to compensate for side-wind or slip of tyres or when performing certain turn manoeuvres on the ground. Also acts as a secondary system in case of system malfunction. In the case of the frictionless system, control of alternate braking is more simplified and more responsive than in the case of friction systems. Anti-skid system is normally utilized in this mode, but can be turned-off and specific malfunctions automatically trigger the switch-off of the anti-skid, just as in the Normal braking mode.

3.3. Emergency/Parking braking

Each wheel has its own EBDU, providing redundancy in the system. However, as the wheels have to actually rotate to provide braking torque, this configuration on its own cannot be used as a parking brake, which is a requirement for airworthiness certification. As a result a simple form of friction brake is integrated into the design, which is electrically actuated between released and locked position. As it does not rely on hydraulic power, the aircraft can park for an indefinite amount of time without re-pressurizing the hydraulic accumulators, as with the case of current systems.

The same feature can be used as an "emergency one use" friction system, designed to stop the aircraft only once in its lifetime. As it only has to survive one landing cycle, it can be made significantly lighter and simpler than the current brake mechanism. After it is used during an emergency landing, the emergency brake has to be replaced, but it is a small price to pay for the safety of the aircraft and its passengers.
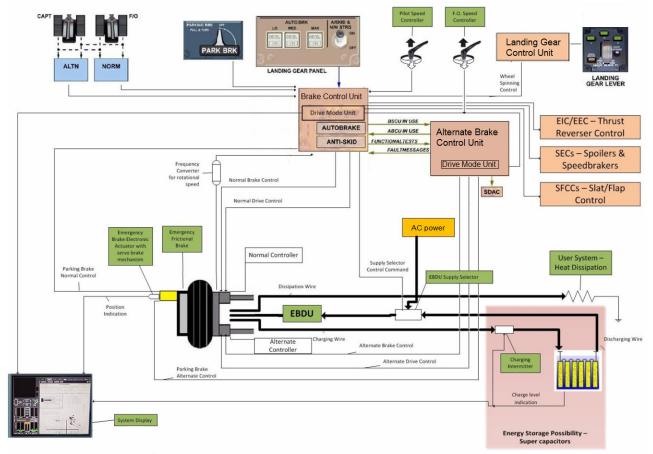

Fig 7. Electromagnetic Brake/Drive Unit system architecture

3.4. Drive mode

In drive mode three main functions have to be performed:

Wheel spin-up: by giving rotational speed to the wheel before landing, the tires' shock load can be significantly reduced, increasing the achievable traction between the tyre and the runway just after touchdown, while also reducing tyre wear thus increasing life.

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Reversing: this function allows the aircraft to operate independently near terminals without the need to purchase the services of a push-back tractor. Although some turboprop aircraft are capable of reversing by setting the propeller angle, it is not a frequent or desirable activity, as it has the potential to feed exhaust gases back through the intake, which is detrimental for the life of the power-plant. Reversing under own power not only saves the cost of the hire, but speeds up operations, as there are no more delays waiting for the tractor, also reducing the chance to miss the take-off slot and pay fines to the airport. As a reference García-Chico investigated the taxi efficiency of aircraft: on a typical winter day in London Heathrow, the average time spent on the pushback operation is 6 minutes. This value might not seem too high, but during the life of the aircraft, this leads to additional costs, which can be saved using the EBDU. Having self-powered reversing capability can be essential for military aircraft, where there can be potential requirements to operate without ground support.

Taxi: the EBDU has the potential to drive the aircraft both taxiing in or out. The electric power can be provided by various sources:

– Main generators (take-off from primary power)
– On-board power storage

By driving the two wheels in different directions, the aircraft also gains the ability to significantly reduce its turn radius, somewhat similar to tracked vehicles.

During normal operation, the braking is done by the EBDU systems, mounted on each main landing gear. The location of the EBDU would be hub mounted, like the Carbon Brakes at current models. Previous studies in this field identified packaging issues, which would have to be investigated further. The system also allows the possibility to install brakes in the nose landing gear, but as they only carry about 6-10% of the aircraft's weight, they would not provide significant benefits.
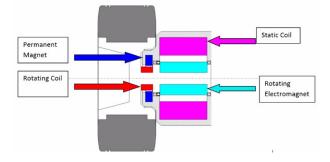

Fig 8. EBDU Cross-section, and its main components.

Ultra-capacitors, if present, could be in the wing body fairing. In this way, the required wiring could also be reduced. The Charging Intermitter would be next to the ultra-capacitors, along the EBDU Supply Selector. The Frequency Converter could be installed on the EBDU, as a part of the motor's controller.

Heat dissipater elements could be installed on the landing gear strut or any large area such as the lower fuselage or wings. It requires further investigation to see the compatibility of these locations, as the heat load must not compromise the structural integrity and thus safety of the airframe.

The power required to operate the EBDU in motor mode also needs to be evaluated for sizing purposes. Assuming an average airport load, a 6000 m and 17 min taxi run is defined as the design case. In order to propel the aircraft, the motors have to produce 8,71 kW of power and a torque of 209 Nm. The total energy required to taxi is 3,14 MJ, which does not take into account potential recoverable kinetic energy during taxi. These figure, along with the values calculated for the brake performance form the basis of the electric machine sizing estimation.

4. ECONOMIC AND ENVIRONMENTAL ADVANTAGES

As air traffic is increasing, emissions at airports becoming an ever serious issue. Significant amount of ground level pollution is generated by the long taxi durations due to congested airports. It is not only gaseous emissions that cause trouble, but also the sound emissions. Jet engines operated at ground level, especially if performing many "speed up and slow down" manoeuvres, are noisy, inefficient. Due to this, today it is the aim of many projects to try to reduce the footprint of ground aircraft operations.

Many studies are concerned with "green" taxiing (for example the work of Dzikus, Fuchte, Lau, Gollinch). Proposals range from using a single engine to various forms of electric taxiing: either an electric tractor or an integrated electric motor. According to Airbus publication by Nicolas, integrated electric drive systems have a potential of reducing fuel burn in the case of short haul flights. An example system for an airliner has an estimated weight of 400 kg, and achieves a saving of 74 kg of fuel compared to a single engine taxi operation (500 NM flight). Based on data provided by Airbus engineers, the fuel penalty for the A320 can be estimated as 82 kg / 1000 kg / 1000 NM for any additional mass taken on-board. Similar figures are evaluated for the concept demonstrator aircraft to enable the investigation of concept feasibility.

Based on the review of electric units' power and energy density, 3 main scenarios were identified to estimate probable future values. Table 1 shows the proposed 3 future scenarios; pessimistic, baseline and optimistic, and the corresponding energy and power densities.

Table 1. Possible future electric device scenarios

Scenario	Pessimistic	Baseline	Optimistic
Power density Motor/generator Stationer load [kW/kg]	1,5	2,5	8
Power density Motor/generator Short load [kW/kg]	3,5	8	12
Power density Eddy current brake [kW/kg]	3,5	4	5
Power density Ultracapacitor [kW/kg]	1,7	2,5	3,5
Energy density Ultracapacitor [kJ/kg]	3,6	8	18

Based on the identified densities, it can be predicted whether using the EBDU system with and without energy storage would yield a net fuel saving or penalty. Assuming typical SFC values for the aircraft's powerplants and APU, the fuel breakeven study can be performed for the various scenarios. It is assumed, that there is a fuel saving due to not taxiing with the primary power system, rather relying on the APU to provide electric power, ideally more efficiently, to the EBDU. Any fuel penalty due to the added mass of the EBDU system will offset this saving, and will determine the suitability of the concept.
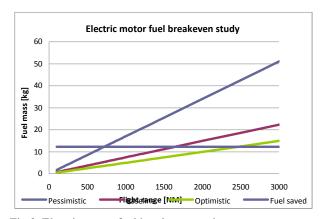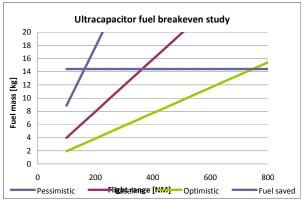

Fig 9. Electric motor fuel breakeven study

Based on the graphs shown on Fig 9, it can be said, that even the pessimistic case would result in a small fuel saving up to about 700 NM range. Optimistic predictions show a beneficial effect up to about 2400 NM, which is over the design range of the aircraft, always resulting in net fuel

saving. Saving kerosene would directly result in reduced pollution of air and water around airports.

Fig 10. Ultracapacitor fuel breakeven study

Fig 10 shows the study investigating the breakeven point of the ultracapacitors added on top of the EBDU, with respect to cruise range. As it can be seen, even with an optimistic scenario, the ultracapacitors only provide a net fuel saving under about 750 NM range. This is due to the fact that although high-tech, the energy storage system is still very heavy, thus imposes fuel penalty. As the design range of a PC-24 is 1950 NM, using the ultracapacitors, would reduce its useful range considerably, or would pose a significant fuel loss, even in the most optimistic of cases when flying long missions.

If a business jet investigated is equipped with Auxiliary Power Unit (APU), relying on the APU instead of the main generators also provides a reduced sound signature for the aircraft during taxi. This however is not the greatest advantage, as the noise emitted during taxiing is a fraction of the take-off sound signature. However, the EBDU has a more significant effect during landing. Electric machines do not experience the high amount of wear as a friction system would, thus it is not required to minimise the use of the brakes. As a result, the aircraft can rely more on the landing gear brakes, and utilize the thrust reverser less, or even neglect its use. This would allow an aircraft to land with significantly lower noise signature, providing the possibility for night operations, making it more favourable in the eyes of airlines. The system might even make the use of thrust reversers obsolete, saving further weight on the aircraft. The amount of noise reduction was not studied in this report.

5.   RELIABILITY AND SAFETY

Electrical machine review

Typical failure rates for electric motors (for example in the study of Penrose et al.) are between $2.5 \cdot 10^{-5}$ and $4 \cdot 10^{-5}$ per hour. The study of the failure of electric motors is a complex field, as each component has different probability of failure.

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The main causes are usually classed as bearings, windings, rotors, and other. Grasselli investigated reliability of standby generator systems, which although are more complex and contain many additional components, are more representative due to the fact that they are not used continuously, but when they are turned on, they have to reach peak power in a short duration of time. From their reported yearly failure rate, a $2.85 \cdot 10^{-5}$ per hour failure rate can be calculated, which agrees well with the previous findings. Thorsen and Dalva published survey of electric motors used in offshore oil industry, which power ratings range from 0.5 up to 25 MW, so definitely covers ours power category. They investigated the effects of many factors on the failure rate of the electric motors, including number of starts. The motors started up to 10 times a day (corresponding to short haul airliner operations) showed a failure rate of $5 \cdot 10^{-6}$. It has to be noted, that most of this equipment is probably immobile, so would have higher provisions of safety (and also higher mass) than the motors utilized in the concept.

It is airworthiness requirement to have system redundancy on the aircraft, especially in safety critical systems such as the brakes. Our proposed concept features multiple redundancies:

- Each landing gear has a separate EBDU, which operates independently from the others
- The control signals are triple or quadruple redundant, with fault tolerant design
- The rotor and stator coils in the EBDU can be sectioned, acting as independent circuits, so that one failure would only reduce the peak performance of the unit, but could still operate at reduced power.
- Emergency friction brake system is installed on every EBDU. Its actuator could connect to the vital power system or has its own energy storage unit.

In addition to being redundant, the system has to be fail-safe. The EBDU is assumed to fail in the following three modes:

- Total loss of braking power
- Application of full braking power
- Undesired drive actuation.

From these three modes, if any, only the total loss of braking power is desirable. Differential braking can compensate for the loss of one brake unit, and the aircraft can still be stopped at an increased distance. However, the other two modes could result in total loss of control. As the system is controlled by electric signal, it is simple to include sensors, which can monitor system health and recognise signs of malfunction. These sensors can then switch the EBDU to passive mode, preventing dangerous operation. This can be achieved by power electronics or circuit breakers for example. The same sensors can also be used to enable maintenance by condition rather than pre-planned intervals, as for example bearing wear can be easily recognised by the change of vibration characteristics in the unit. This data can be fed to an Integrated Vehicle Health Management (IVHM) system if it is installed in subsequent generations of the aircraft.

Removing the carbon friction discs also eliminate most of the key issues with current brakes; disc warping and fading. As the energy is not dissipated at the small brake surfaces, rather at a larger area further away where there are better conditions for heat transfer, the heating of the whole area is reduced as well, resulting in longer components life, also less heat load to the tyres. The high heat generated by the brakes, especially during a rejected take-off, can seriously damage the tyres or the aircraft or activate the emergency valves causing the tyre to deflate. Further environmental and health benefits can be achieved by removing the friction system, as the EBDU does not emit the fine carbon particles resulting from the wear of the discs, eliminating the health risk for the environment and maintenance personnel.

The kinetic energy of the aircraft has to be either stored or dissipated, but in any case it has to be routed away from the EBDU in the form of electric current through conductors. Depending on the area chosen as the dissipater position (fuselage, wing surface, landing gear strut), these conductors might have to be routed near fuel tanks or other sensitive equipment. As such, adequate insulation must be considered for safety.

Cooling systems have to be implemented for the ultra-capacitors and any auxiliary equipment. This can be done by installing ventilation systems. The source of the cooling air would be the Cabin Ambient Air, which is already cooled by the ECU(s). During flight, the ventilation could be achieved without a fan, in the same way as the ventilation of the batteries: by installing a Venturi outlet, the pressure difference between the cabin pressure and ambient pressure would create a continuous flow. For ground operations, installation of a blower fan is necessary, because the pressure difference is not high enough to create the cooling flow. During braking, higher ventilation performance is necessary, which can be sustained by the power generated by the EBDU.

Fire protection of the enhanced system requires a smoke detector in the outlet ventilation duct, to detect the electric fire. To prevent false fire warnings, redundant smoke detection system has to be installed. The monitoring of the detectors would become the Smoke Detection Control Unit's function, so an additional control circuit has to be installed. Because the stored power of the Super Capacitors is much higher than the avionic compartments', the separation of the systems wouldn't be enough. Fire Extinguisher System also has to be installed in the area. Smoke Detection System would send signals to the cockpit, and would automatically activate the Extinguisher, to reduce the delay between the fire warning and the action. In the case of any failures, the ultra-capacitors would be separated from the secondary power system of the aircraft immediately.

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6. CONCLUSIONS

To summarize, the proposed system is capable to provide alternative solutions to the current friction brake systems. Additional advantages include higher safety and reliability conditions, electric taxiing, wheel spinup before touch-down, and the potential regeneration of the wasted kinetic energy, which is always dissipated during braking in a friction brake system. As there are no electrical devices yet designed especially for this application, the design proposal is still at conceptual level. Considering the benefits of the concept, it can provide ground for further investigations and research work, especially with the high maturity and continuous innovation in the field of rotating electric machinery. Thus as indicated, using this concept can help to reduce the environmental impact of aviation, and provide a greener, more sustainable transport solution.

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