Conceptual Design of an Energy Harvesting System for Aircraft Landing Gear

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Abstract

Current aircraft generate a substantial amount of unused energy. There is a potential to harness and use some of this energy. Energy harvesting systems aim to reduce the electrical power required on an aircraft, and more broadly will help in creating sustainable forms of power. This paper explores different methods of harvesting energy and considers how to implement them into harvesting energy from aircraft landing gear. This paper includes considering existing systems that are used in an alternative way. The paper develops a number of conceptual ideas based upon this research into one conceptual design of an energy harvesting system. The finalized conceptual design includes details of the entire system, including energy conversion, energy capture and storage, and energy usage.

1. Introduction

The engineering industry is searching for new ways of scavenging energy due to the detrimental effects of current technologies on the environment. Scavenging energy reduces the amount of energy required, thus reducing this effect (assuming this energy is initially generated using non-renewable resources). Aircraft contribute to 4.9% of global warming. This figure is set to rise due to air traffic doubling every decade [1]. By reducing the effect of aircraft on global warming now, the effect of aircraft on global warming in the future will be minimised.

The landing gear and landing gear systems are subject to the most severe environments witnessed by aircraft [2]. As such, a large amount of energy is dissipated into the atmosphere. By harvesting some of this energy, the system will use more sustainable forms of power.

This project uses a systems engineering approach to find the most appropriate system. This system will be fully designed and analysed within the limited scope of this project. Any further development will be clearly stated within the report.

The project will conduct a requirements based engineering approach into designing an energy harvesting system. Research has been conducted into the importance of requirements based engineering, and the effect this has on the success of a project. This research concluded that the majority of executive managers were able to complete successful projects with a clear set of requirements [3]. These executive managers stated that 80% of the failed projects, when undertaken using requirements based engineering, were cancelled due to complications experienced during the concept evaluation stage (as opposed to further along in the development process) [4].

A feasibility study has been conducted defining the project aims and objectives, and a time plan for the major activities conducted throughout the project, as well as the commercial viability of the project.

1.1 Project Aims

- To produce a conceptual design of a system that will allow energies generated by the landing gear of an aircraft to be harvested and used in flight.
- To discuss the benefits of using such a system in industry and make any justified recommendations from the investigation.

2. Initial Concepts of Energies Generated by Aircraft Landing Gear and Energy Conversion

2.1 Thermal Energy from Brakes

During landing, the hottest parts of the brakes typically reach between 400-600°C under normal braking conditions [5]. These brake temperatures are generated by large amounts of braking in small amounts of time. This thermal energy is lost into the atmosphere. To speed up this process, brake cooling fans are used and require energy to rapidly cool the brakes, to allow a faster turnaround time.

The cooling profile of the brake deduces the amount of power dissipated from the brakes. This cooling profile can be predicted using the formula:

$$(T_f - T_{amb})/(T_i - T_{amb}) = \exp(-t/K) \tag{1}$$

Where:
T_f = Brake Temperature prior to take-off (°C)
T_i = Brake Temperature after braking (°C)
T_{amb} = Ambient Temperature (°C)
t = time (s)
K = Cooling Constant

This prediction has been proven to correlate very closely with the actual cooling profile (<1% error) [2]. This cooling profile can be used to calculate the time required for the brakes to cool (without brake cooling fans fitted).

Note: A 'K' value of 6,500 can be assumed for worn brakes, 7,000 for partially worn brakes and 7,500 for new brakes with no brake cooling fans fitted.

The thermal energy of a brake can be calculated by using the equation:

$$E_{Thermal} = mc\Delta\theta \tag{2}$$

Where:
$E_{Thermal}$ = Thermal Energy (J)
m = Mass (kg)
c = Specific Heat Capacity ($J\cdot kg^{-1}\cdot K^{-1}$)
$\Delta\theta$ = Change in Temperature (°C)

The power dissipated is calculated by multiplying the energy by 3600 (to convert the value into kW·h, a known measurement of power for battery storage and component power usage).

By making the assumption that the brake has a mass of 146kg (based on an Airbus A340-700) [2], the specific heat capacity of Carbon brakes being $J\cdot kg^{-1}\cdot K^{-1}$ and considering brake temperatures of between 400-600°C, Figure 1 can be produced. The energy calculation is halved to consider the average heat distribution of the brakes (and not just the hottest part of the brake).

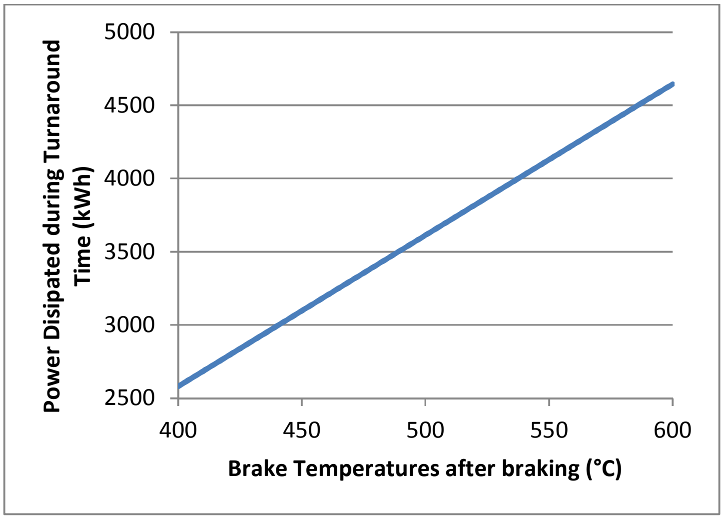

Figure 1 - Power Dissipated due to Brake Temperatures (no brake cooling fans fitted)

By using the temperature differential between the brakes and a point in the landing gear, there is a large enough temperature difference to create a significant amount of energy. This energy can be converted from thermal to electrical using a thermal generator.

For the applications of this project, it is likely that the aircraft are fitted with brake cooling fans. The energy harvested could be used to power these brake cooling fans. As such, the cooling profile would be significantly less than previously stated. To calculate the cooling times for brake cooling fans, the same cooling profile equation is used. The value for the cooling constant (K) can be assumed to be in the region of 800-1000. For the purposes of this analysis, a K value of 800 is used for new brakes, 900 for partially worn braked and 1000 for fully worn brakes. Once this time has been calculated, it is assumed that the thermal energy dissipated by the brakes with brake cooling fans is released at the same flow rate as the brakes without brake cooling fans fitted. As such, to calculate the thermal energy available to harvest when brake cooling fans are fitted, the thermal energy is multiplied by the ratio of cooling time for the brakes with brake cooling fans-cooling time for the brakes without brake cooling fans. By converting this value into the power dissipated (in kWh), a known measurement of power for storage and component power usage can be used to perform a more detailed analysis, and Figure 2 is able to be produced.

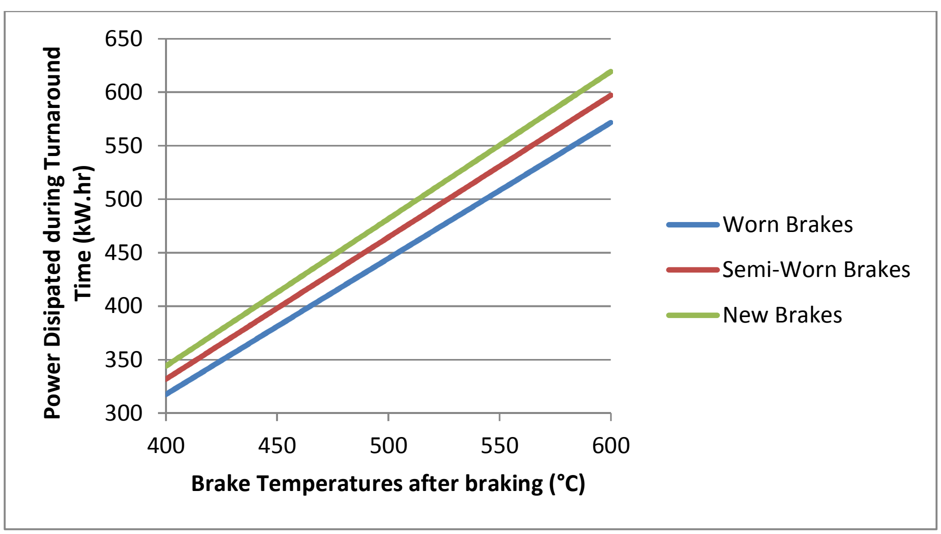

Figure 2 - Power Dissipated in Comparison to Brake Temperatures (brake cooling fans fitted)

A thermal generator takes a temperature gradient and converts it into electrical power. This thermal energy is radiated from the carbon brakes. To gain an accurate radiative heat flow, Stefan-Boltzmann's law can be used. This law states:

"The Stefan-Boltzmann's law is a relation which describes the power radiated from a black body in terms of its temperature. It states that the total energy radiated per unit surface area of a black body across all wavelengths per unit time (also known as black body irradiance or emissive power) is directly proportional to the forth power of the black body's thermodynamic temperature" [6]

From this law, the following radiative heat flow equation can be obtained [7]:

$$Q_r / t = \sigma \cdot \varepsilon \cdot A \cdot \theta^4 \tag{3}$$

Where:
Q_r = Radiative Heat Flow ($J \cdot m^{-2}$)
t = Time (s)
σ = Stefan's Constant ($5.6703 \times 10^{-8}\ W \cdot m^{-2} \cdot K^{-4}$)
ε = Emissivity (0.95 for carbon-carbon brakes)
A = Surface Area of the radiative device
θ = Temperature (K)

For the purposes of this analysis, it is assumed that the heat is radiated at a constant rate dependent upon the area of the carbon. It is assumed that the radiation flow rate is uniform around the carbon brakes and dissipates at a constant rate. The assumed values are a wheel radius of 23" (0.5842m) and a brake width of 0.3m [2]. The analysis showed a minimum area required by the thermo electric generators to be $0.002m^2$. This value has considered the expected efficiency rate of the system to allow the minimum power requirements detailed in Appendix B during a worst case scenario of brake temperatures and brake wear. The analysis has not considered the effect of the environment (wind etc.) as this is assumed to be negligible.

To calculate this value, the Carnot efficiency of the system is considered. The equation below is used to conduct this calculation, and the assumed values are detailed below. The minimum efficiency (assuming worst case scenarios) is calculated to understand fully the number of thermoelectric generators required.

$$\eta = \Delta\theta / \theta_{max} \tag{4}$$

Where:
η = Carnot Efficiency
Δθ = Temperature Differential (K)
θ_{max} = Maximum Temperature (K)

Assuming a temperature differential of 380°C and a maximum temperature of 400°C, the Carnot efficiency is assumed to be 56%.

A thermoelectric generator applies a temperature differential to a generator to allow a voltage to be supplied. The larger this temperature differential is, the larger the output power. This output power can be very limited, and therefore multiple generators may be required to generate larger amounts of power for larger uses. This energy could be stored prior to being distributed.

2.2 Vibration Energies During All Flight Phases

During all flight phases, the landing gear is subjected to some level of operational vibrations. All landing gear components undergo vigorous vibration tests to ensure that the component is remains operational during the environment associated with the landing gear system.

It is difficult to quantify the levels of energy dissipated through vibrations. To gain a level of understanding into the amount of power dissipated and the amount of energy able to be harvested, a simulation is required.

For standard vibrations, the RTCA DO-160F [8] gives details of the vibration levels required to test. These vibration levels are extreme values and not typical values, and as such a safety factor of 0.5 is assumed. For standard vibrations for all equipment stored within the landing gear bay, it is assumed that curve W, on Figure 3, will incorporate all of the vibration energies associated with landing gear during all flight phases (including landing).

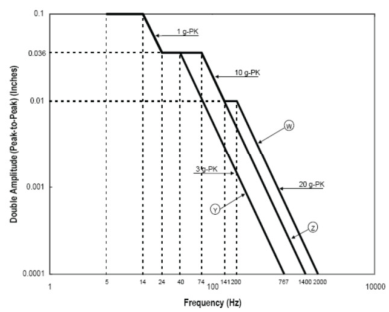

Figure 3 - Standard and Robust Sinusoidal Vibration Test Curves for Equipment Installed in Applicable Zones in Fixed-Wing Aircraft with Turbojet or Turbofan Engines and Unducted Fan Engines [8]

These vibrations can be modelled using a spring mass damper. If the landing gear is to be displaced by an angle (θ), the following equation can be used (modelled in Figure 4) [9]:

(5)

Where:
k = spring constant (very large) (N/m)
m = mass (kg)
l = play in the system before the spring affects the motion of the landing gear (m)
r = distance from the landing gear attachment and the landing gear uplock (m)
R = distance from the landing gear attachment and the COG of the landing gear (m)
θ = angular displacement
F = Force (N)

This equation assumes that θ is positive when displaced upwards, and assumes:

$$\Sigma F = F - mg \quad (6)$$

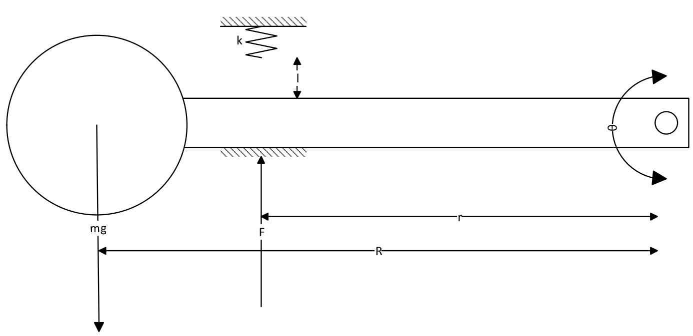

Figure 4 - Spring Mass Damper Model for Vibrations

$$\omega_n = (k/m)^{1/2} \quad (7)$$

$$\zeta = c / (2 \cdot m \cdot \omega_n) \quad (8)$$

$$\eta = \omega / \omega_n \quad (9)$$

Where:
m = Landing Gear Mass (kg)
c = damping coefficient
k = spring stiffness
F = Force (N)
ω = frequency (rad/s)
ζ =Damping Ratio
x = displacement (m)
ω_n = natural frequency (rad/s)
η = frequency ratio

Using the equation:

$$P = \partial E/\partial t = F \cdot v \tag{10}$$

Where:
P = Power (W)
E = Energy (J)
t = Time (s)
F = Resultant Force after damping (N)
v = Velocity (m/s)

Enough information is available to provide a simulation of Figure 4 to detail the power dissipated during disturbances causing vibration in flight.

A spring mass damper model is used to simulate the displacement and in turn the energy and power able to be dissipated by such vibrations. During cruise, any vertical disturbance must first overcome the mass. This is because the mass is acting down on the uplocks. This analysis currently only considers the vibration energies associated with the entire landing gear load. In reality, it is possible to harvest energy from landing gear components vibrating. These smaller masses will be subject to more vibrations as the mass of the units are significantly smaller than that of the entire landing gear. In turn, this will create more energy able to be harvested. This is modelled in Figure 5.

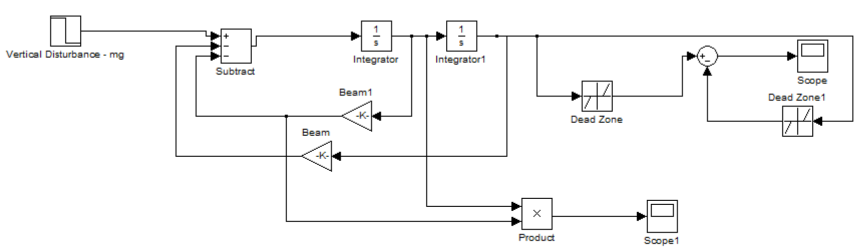

Figure 5 - Simulink Model for Power Output of Vibrations

The results of the Simulink model produce two graphs, one showing the vertical displacement of the landing gear (Figure 6) and one showing the power output of the device (Figure 7).

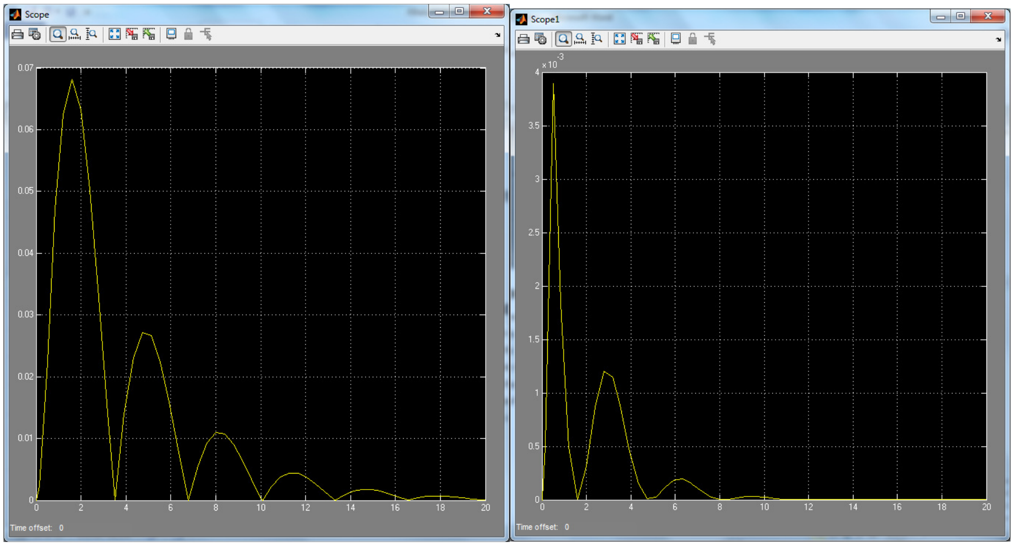

Figure 6 & 7 - Landing Gear Displacement & Power Available to Harvest Due To Vibrations (Respectively)

This analysis has assumed nominal vibrations during flight, and as such the values provided can be assumed to be an average for the flight. The power available to harvest is 0.00389W of electricity at any given moment. To gain the energy required to power the brake cooling fans, the flight must have a duration that is significantly larger than the flight times.

2.3. Shock Loading on Landing Gear during Landing

The landing gear is subjected to high level shocks during landing. These shocks will consider both the mass of the aircraft when landing, and the descent rate of the aircraft. The equation for this energy is given as:

$$E_{Kinetic} = 0.5 \cdot m \cdot v^2 \tag{11}$$

Where:
$E_{Kinetic}$ = Kinetic Energy (J)
m = Mass (kg)
v = Velocity in a given direction (m/s)

The shock absorber within the landing gear must overcome the mass of the aircraft. This energy is distributed over time (dependent upon the damping of the shock absorber), however the mass for a landing due to the downward force is constant. The velocity of the aircraft is dependent upon the descent rate of the aircraft. The typical descent of an aircraft when landing is 300fpm. This corresponds to 1.524m/s. Figure 8 displays the potential kinetic energy dissipation for a range of aircraft weights (including the A318 to the A380). In reality, the potential energy of the aircraft and the mass loading on the tyres and suspension is a contributing factor, however for the purposes of this analysis this has been assumed to be negligible.

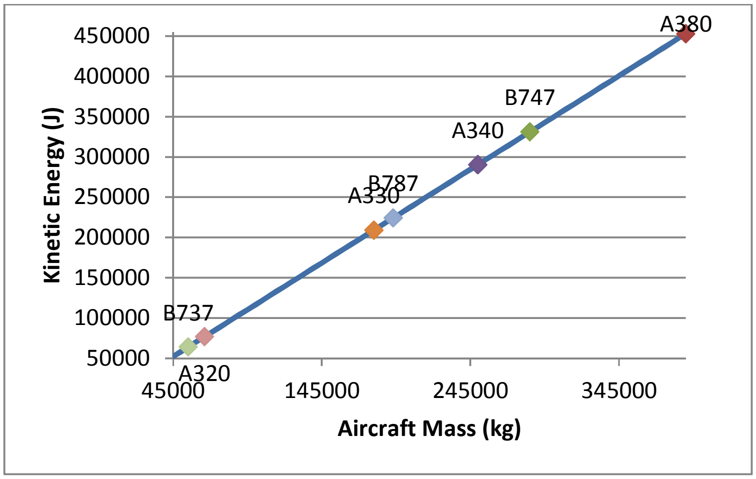

Figure 8 - Energy Dissipated due to Shock Loading during Aircraft Landing

The power dissipated during this landing is calculated by multiplying the energies by 3600 (to convert the value into kWh, a known measurement of power for storage and component power usage). Without considering the timescales for shock loading, these calculations can seem exaggerated. As such, Figure 8 considers the Kinetic Energy as opposed to the power dissipated (in kWh).

This energy can be harvested by using electromagnetic generators. The electromagnetic generators can be implemented to work with the shock absorber assembly and convert the shock loading into electrical energy. Although a large amount of energy is produced, the amount of power is very limited as the shock loading occurs over a very small amount of time. The calculations detailed in Figure 8 are the energies for the entire aircraft, so the values would be spread over the number of landing gear.

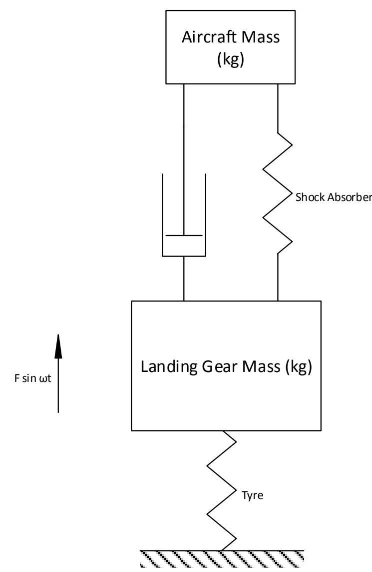

Figure 9 - Spring Mass Damper Model for Shock Loading

Figure 9 displays the spring mass damper model for shock loading. During development this may be used to create a Simulink model to calculate the power dissipated in the given environment and can be used to determine the actual power harvested and able to be output by the system. This calculation will only be pursued should the concept be chosen for development.

3. Initial Research and Concepts of Energy Capture and Storage

3.1 Battery Storage

The main limitation with battery storage is the weight implications associated with the power required. Batteries store DC electricity, which can be used within current brake cooling fan systems. As such, batteries are a valid form of energy storage for the purposes and applications of this project.

Common household batteries are Nickel Cadmium (NiCd) or Nickel Metal Hydride (NiMH). These batteries hold approximately 50Wh/kg and 90Wh/kg respectively. This would equate to 2.5kg and 1.4kg per brake cooling fan. On an Airbus A380 with 16 braked wheels, this would be an additional 40kg and 22.4kg (which are considered significant additional weight).

An alternative to these batteries are Lithium Polymer batteries (LiPo). Current technology allows double that of NiMH batteries per kg (180Wh/kg). This would be 0.7kg per brake cooling fan, and for the A380, 11.2kg of weight. This is still considered significant additional weight. New Li-Ion technology allows up to 400Wh/kg [10]. The release of these batteries will coincide with the potential development of this system. As such, the weight for the A380 would be reduced to 4.8kg. This additional weight is acceptable for the implementation of a system.

In reality, industry defined battery sizes would be used. The standard sized batteries using the new Li-Ion technology have a mass of 365g and dimensions of 97mm x 190mm x 10mm. These batteries hold between 137Wh and 152Wh dependent upon the number of cycles they are subjected to. The battery has been fully tested and is expected to remain operating after 450 charge cycles, and is able to operate safely within conditions of -30°C and 270°C [10].

3.2 Capacitors

Capacitors are a viable form of storing energy for relatively small amounts of time. Capacitors are a more beneficial solution in terms of the weight saving, cost and maintenance. The limitation that capacitors carry is the amount of energy able to be stored. This limitation is only valid for the system if the power required exceeds the amount of power stored at any given moment.

Brake cooling fans require 250W of power at any given moment. The use of capacitors within the system allows a constant power output assuming there is a constant rate of charge. If energy is supplied to the system at a variable rate, the power output of the capacitor could change. This change is dependent upon the size of the capacitor and the capability of the capacitor to retain excess charge for a longer amount of time. A typical discharge rate of a capacitor is very low. For applications such as shock loading, where there is a huge amount of energy in a short amount of time, it is likely that the capacitor will not be able to store the majority of the energy. For applications such as thermal energy, where the rate of energy dissipated is relatively more constant, the capacitor would be able to supply a constant power output to a given application.

In an application such as shock loading, batteries may also not be able to hold such a large amount of energy in a short space of time. It may be required that a capacitor is used in conjunction with a battery to slow down the rate of charge applied to the battery, increasing the efficiency of the system.

4. Initial System Level Concept

For the system to provide useful energy for a given purpose, the energy must be stored efficiently and distributed in an equally efficient manner. To ensure this is possible, the energy supplied for from the source must be converted into a manageable pre-defined form (with a given voltage, current and therefore power output) to ensure no unnecessary strain is put on the storage device, and the energy is being supplied at a constant and steady rate. Similarly the output from the storage device must be converted to ensure the correct power is supplied for the given application. This might be in AC or DC form.

Figure 10 shows the system level architecture including all subsystems. It displays how each concept will feed into the next. The energy source corresponds to the aircraft landing gear energy dissipated to the mechanical energy conversion subsystem. Once this mechanical energy is converted into electrical energy, the energy must be converted into a useable form for the energy storage device. The stored energy is able to used and distributed when required for any given application. Once leaving the storage device, the electrical energy will undergo one final energy conversion to ensure the desired output power is supplied for the application.

The only major consideration necessary during the product development and evaluation is the efficiency at each of these stages. The efficiency of the system is critical as it will define the energy output of the entire system.

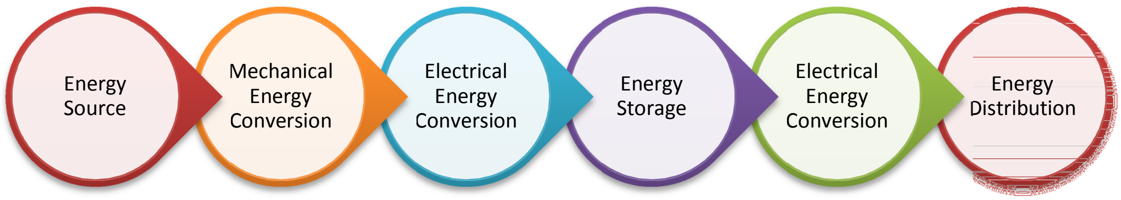

Figure 10 - System Level Architecture

5. Concept Evaluation

Each concept has been fully evaluated against a pre-defined detailed system design specification. Following this structured evaluation method, a conclusion with an evaluation summary has defined the feasibility of the concept and the development activities required to ensure the concept meets the specification. Only the relevant requirements were evaluated for each concept.

This evaluation has been conducted in accordance with the environmental conditions and test procedures for airborne equipment DO-160F [8]. An analysis has been undertaken to review the test procedures for different locations on the aircraft, and an assumption has been made as to the feasibility of the components compliance with the specified requirement. Should this system/component be further developed to be introduced onto aircraft, these requirements must be proven by analysis, test (or similarity test) or both. The purpose of this evaluation is to give an initial indication of the feasibility of the system.

5.1 Energy Generation and Conversion

There is a substantial amount of energy can be harvested by implementing thermoelectric generators around the brake area. This energy source and mechanical energy conversion seems like a viable concept as there is no requirement that the system does not meet (pending some development activities). The only concern of this system is the actual temperature difference experienced by the thermoelectric generators, and the efficiency of the system. Both of these will be considered during concept development.

The implementation of electromagnetic generators to harvest energy due to the vibrations experienced in flight will only harvest a limited amount of energy. This energy source and mechanical energy conversion could be a viable concept if implemented in another area of the aircraft (that is not limited to landing gear). The highest levels of vibrations experienced by the aircraft are during take-off and landing when the landing gear is extended [2]. This limits how effective the system is. Although this is the case, if the system was able to be incorporated into another system with minimal development, integration and maintenance (and additional cost and weight implications), the system could improve the amount of energy harvested and as such improve the feasibility of the system. This analysis has not included the vibrations experienced during taxiing.

The implementation of electromagnetic generators to harvest energy due to the shock loading experienced during landing will only harvest a limited amount of energy. This energy source and mechanical energy conversion could be a viable concept if implemented in another area of the aircraft (that is not limited to landing gear). This energy is not large enough as the efficiency of the system would be too small due to the large amount of energy dissipated in a small amount of time. Although this is the case, if the system was able to be incorporated into another system with minimal development, integration and maintenance (and additional cost and weight implications), the system could improve the amount of energy harvested and as such improve the feasibility of the system. This analysis has not included the vibrations experienced during taxiing.

Following the evaluation of the given concepts, the only concept able to provide sufficient power and provide a large financial benefit to customers is implementing thermoelectric generators to the braking system to allow the harvesting of thermal energy during braking. This is the only concept considered during the development process, and as such all development activities associated with the remaining two concepts are not considered.

5.2 Energy Capture and Storage

Battery storage is a more desirable concept than that of capacitors for flexibility and feasibility of the system. By using capacitors, the use of the electrical energy is limited. If energy distribution was pre-defined and was not going to be used for any other application, the use of capacitors might be desirable in terms of the cost and weight implications. Due to the limitations defined within this project, and the limited scope, for the purposes of development batteries alone are considered.

5.3 System Level Evaluation

During conceptual ideas, it is not possible to perform a full system level evaluation. It is more beneficial to conduct this evaluation following the development stages of the project and use this evaluation to recommend any further improvements to the designed system.

6. Concept Development

6.1 Thermoelectric Generator

An industry standard thermoelectric generator must be used for the system. This thermoelectric generator must be capable of converting sufficient heat energy at an acceptable efficiency. For the purposes of this analysis, it is assumed that five times the required output power is needed. This should ensure a sufficient system output power (due to the energy lost during conversion and storage). The thermoelectric generator must also satisfy all environmental and safety requirements.

There are currently very few thermoelectric generators able to operate over and above the high temperatures of the brakes. This is due to the affect temperatures have on thermoelectric materials. New technology has enabled the development of Calcium/Manganese (CMO) thermoelectric generator modules. This new material allows up to 900°C on the hot side. The use of these thermoelectric generators will not degrade the life. The modules are likely to last up to 50 years [14] (with the life of an aircraft being 25 years). The details of this component are contained within the data sheet for part CMO-32-62S [14].

For the worst case scenario, considering brake temperatures of 400°C with brake cooling fans operational for 30 minutes, 110 units are required. Assuming a wheel radius of 23” using standardised carbon rotor brakes, there is an outer area allowing for 224 thermoelectric generators to be placed around the circumference of the disks. This will produce a minimum of 510W assuming the system is fully operational. This includes the inefficiencies of the thermoelectric generators.

These generators will be arranged in a 4 x 56 layout. The generators will be placed as close to the end of the brake as possible. This will ensure that the power output remains constant even when the brakes are worn. By implementing these thermoelectric generators in series, 255Wh of electricity can be converted [14]. Following a conversation with an industry expert, it was understood that a larger thermoelectric generator in a defined arrangement could be fabricated at little extra cost.

The use of this thermoelectric generator will not adversely affect the safety of the system. The thermoelectric generator modules are qualified over and above the temperatures detailed within the specification and fully qualified against fire.

5.2 Battery Storage

The chosen Envia Systems battery is qualified against the SAE J2464 safety standard [15]. Although the full qualification has not been completed, a series of development tests have confirmed the new technology is likely to pass on all tests. Following an in depth analysis comparing the requirements for both aircraft and automotive batteries, the requirements and testing detailed within this safety standard meet the majority of safety requirements. The only requirement not met by the standard is the temperature.

This battery must be qualified between -40°C and 70°C for compliance with the SAE standard, and is fully tested by Envia Systems between -30°C and 270°C. The battery must be fully operational during these times. For applications within this system, the battery must be operational on ground, but not in flight. As such, the requirements governed by the safety standard are valid for the batteries application. Further testing would be required to confirm the batteries survival during the temperature extremes. The only limitation posed upon the battery is the location. The battery must be stored away from the brakes. The proposed position of the battery is by the brake temperature monitoring system. This system is housed within the landing gear but outside the high temperatures generated by the brake. The only other position would be in the landing gear bay, however this would require a large amount of excess cabling which could induce efficiency restrictions.

5.3 System Architecture

The finalised system will include an array of CMO-32-62S thermoelectric generators [14]. These thermoelectric generators use the temperature differential between the hot brakes and the ambient temperature (in the best case scenario). These generators will produce an average power of 510W of electricity per braked wheel assuming the system is fully functional, and considering only the hot side of the thermoelectric generator. Should the cold side of the thermoelectric generator be receiving ambient temperature, the power produced would significantly increase. The power captured and converted by the thermoelectric generators will not be constant and as such will not be of a constant voltage or current.

These thermoelectric generators will feed into a DC/DC converter to ensure that the power is transferred along the system at a constant current. This constant current will allow the battery to be charged. The average efficiency of such a converter varies between 80-95% [16]. For the worst case efficiency of the DC/DC converter, an average power of 408W would be supplied to the battery, assuming the thermoelectric generators were fully operational. This would provide a total of approximately 204Wh of electricity to store.

Each braked wheel will incorporate one lithium-ion battery capable of storing a minimum of 137Wh of electricity [10]. Assuming the optimum current is used to charge the batteries (defined by the DC/DC converter), these batteries are capable of storing all the energy supplied by the system, and is capable of sending the same amount of power out of the system (assuming the battery does not reach its electricity storage limit) [17].

The battery will then feed into another converter. This converter depends on the application in which the system is being used. Currently most brake cooling fans are AC powered. In this case, the battery would feed into an inverter to generate AC power at a given current and voltage to power the fan. Newer developments in the aerospace industry have allowed for the production of DC brake cooling fans. In this case an additional DC/DC converter would be implemented to supply power to the fans. In both cases, the efficiency can be assumed to be 80%. Assuming the losses in wiring are negligible across the whole system, the total power output of the system would be 163Wh. This assumes that the battery never reaches being fully charged, and therefore the battery stores all power provided by the DC/DC converter. Using these calculations, for the worst case scenario of energy produced, and the longest duration at which the brake cooling fans would be operational, the efficiency of the wiring must be at least 77%. During the final integration of the given system, this efficiency should be considered when defining the wiring characteristics.

A failure mode effects analysis has been performed. This analysis proves the possible failures of the system and the severity of these failures. Any failures detailed have compensation methods and failure detection modes. The analysis has allowed further development to be defined to ensure compliance with CS25 [11].

7. Conclusions

The project started by outlined some simple conceptual designs for an energy harvesting system. These initial ideas included using thermal energy from the brakes, using the vibrations from the aircraft landing gear when in the retracted position (throughout the flight) and using the shock energy generated during aircraft landing. The conceptual designs also considered the energy storage devices (capacitors and batteries).

These conceptual ideas then used innovative products and technology to consider the feasibility of the solution, and consider how the conceptual idea could be developed into a maximised conceptual design. This conceptual idea and conceptual design was fully evaluated to understand the success of the design. The results of the evaluation showed that the most effective system would comprise of thermoelectric generators to capture and convert thermal energy, and lithium-ion batteries to store the energy.

Upon developing and fully understanding the conceptual components, these components were brought together to enable the system architecture to be designed. The system architecture considers energy dissipation, energy capture and conversion, energy storage and energy distribution.

This system architecture was fully evaluated to understand the overall effectiveness of the system. Assuming the designed system is fully operational, the system will be able to harvest and distribute a minimum of 163Wh per braked wheel. This calculation considers all losses except those due to cabling. The system was designed to be able to power the brake cooling fan for the given wheel. In reality, this figure is likely to be significantly more. The assumptions made within this calculation were a maximum brake temperature of 400°C for new brakes (worst case scenario). In reality, flight tests have proven that brake temperatures are likely to exceed these temperatures. Figure 11 summarises the system level architecture defined above.

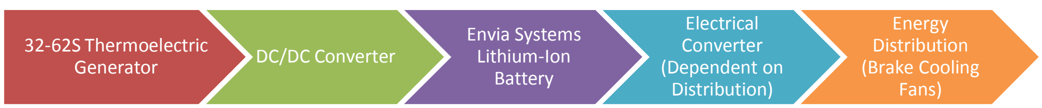

Figure 11 - System Architecture

7. Further Development

The system architecture has been detailed within the contents of this report. This architecture has used requirements based engineering to fully evaluate the individual components and the system in its entirety. The evaluation of the components and system has considered the environmental conditions in which the system will operate. For the purposes of this project, the evaluation has used engineering judgement to demonstrate compliance or non-compliance with these requirements. For the system to be implemented within existing or future aircraft, the components and system must be proven to be compliant with all of these requirements. This proof must be demonstrated by test, analysis or both. This is outside the scope of this project, but is essential for the future development of the system. To ensure sufficient safety margins, and compliance with CS25, it is essential that a further development activity is used to generate a battery management system.

The use of capacitors as a means of storing the required energy has been briefly considered, however the use of capacitors could offer a huge financial benefit over batteries (due to the size, weight and cost implications). Although this is not the best solution for powering the brake cooling fans, if the energy stored was to be distributed to an alternative system, these may provide additional benefit.

To charge the battery and to distribute the electrical power to the given application, electrical converters (such as DC/DC converters) have been used. These have not been designed and evaluated with significant analysis. The use of these converters is dependent upon the application of the energy harvesting system, and the specification of the battery. As these are not defined in detail, this has been unable to be fully investigated. Upon the official qualification of the battery and known application for the system, these converters will be able to be fully explored.

The final application for the system has yet to be defined however there are a large number of electrical systems on board aircraft. As such, a detailed investigation should be conducted to define the application of the system.

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