THERMAL MANAGEMENT OF ELECTROMECHANICAL ACTUATION ON AN ALL-ELECTRIC AIRCRAFT

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Abstract

This report addresses the thermal management of electromechanical flight control actuators on an all-electric aircraft (AEA).

Information relating all-electric aircraft, electromechanical actuators (EMAs) and thermal management concepts is presented and the thermal management problem is explained. Several thermal management system (TMS) concepts were identified, and the best of these concepts were evaluated based on their application to a case study aircraft. A hypothetical aircraft was chosen, representing a possible "all-electric" successor to the Airbus A320 and Boeing 737.

Thermal management issues are one of the remaining barriers to the use of EMAs for primary flight control, as their reliability is highly dependent on operating temperature. The absence of a hydraulic network from an AEA means hydraulic fluid will not be available to dissipate heat from the actuation system. An alternative cooling solution must therefore be developed.

Simple calculations were made which confirm the need for dedicated thermal management of flight control EMAs. The heat output from EMAs of equivalent power to the hydraulic actuators on the Airbus A320 was estimated, using an assumed overall efficiency of 0.84. This formed the basis for the case study design work. Heat pipes, thermosyphons and air-cooled cold plates all appear to be feasible cooling devices for achieving the design temperature requirements set for the EMA (80°C nominal operating temperature and 125°C peak temperature). The mass of the aircraft-level systems was estimated as 49, 34 and 32 kg, respectively, but these values do not include the mass of any cooling air supply equipment.

The use of acetamide as a phase-change material (PCM) for thermal energy storage improves peak cooling performance by reducing the peak EMA temperature to near the PCM melting point. However, it does not result in a mass saving for the case study systems. The design calculations suggest future improvements in the thermal tolerance of EMA components could allow significantly lighter TMS designs to be used.

Further work is needed before a final recommendation can be made regarding the preferred concept for the case study application. This should include a more detailed study of cooling air supply options, a complete system mass and cost estimate, and a trade study to evaluate the EMA reliability improvement from the use of a PCM. However, it is hypothesised that ram-air-cooled cold plates will offer the best solution; based on preliminary mass, cost and cooling performance considerations..

1 Background

The fundamental difference between a conventional aircraft and an AEA is the absence of centralised hydraulic and pneumatic systems from the latter. While this is expected to bring benefits, it also introduces a number of challenges. An electric flight control actuation system (FCAS), also known as a power-by-wire (PBW) system, becomes essential. Elimination of the hydraulic network means hydraulic fluid will not be available as a convenient means of transporting and dissipating the heat generated by the actuation system. Therefore, an alternative solution must be sought to deal with the heat produced.

The thermal management problem is complicated by the fact that the heat produced by electric actuators is highly localised in areas around the actuator motor and power electronics. The actuators themselves are also distributed around the extremities of the airframe, which makes a centralised system difficult to implement. The reliability of the EMA components is critical to the ability of the aircraft to be flown safely and the mean time between failures (MTBF) of the electronic components is particularly dependent on temperature. An all-electric aircraft will therefore require a new method to control the temperature not only of the mechanical components of the electric actuators, but also their electronic control units (ECU).

1.1 Thermal Management for Electrically Powered Flight Control Actuation Systems (FCAS)

Due to the elimination of the hydraulic network as a means of transporting heat, the thermal management of an electrically powered FCAS will inevitably be quite different to that of a hydraulic system. Instead of the heat being conveniently distributed throughout the system via the flow of hydraulic fluid, the heat in an electric actuation system will be highly concentrated in the vicinity of the actuators. This suggests a distributed approach may be needed to control the temperature at the actuator locations. The localised heat, produced near the extremities of the aircraft with no convenient means of dissipation, makes thermal management a much more challenging and important design problem for electric actuation systems [1].

Several studies have looked specifically into thermal issues for electric flight control actuators [2; 3; 4; 5]. The focus of these studies has generally been the simulation, laboratory testing or development of a particular concept to transport the heat from the actuator motor and power electronics. Very few published studies have focussed on evaluating several different system concepts for a particular application. Many of the prototype systems have been designed to transport the heat to nearby aircraft structure and ultimately dissipate it by convection from the aircraft skin. The components have all been designed as single EMA cooling solutions; so will need to be installed on every actuator individually. The testing done on these systems to date appears to have shown positive results and suggests that several different approaches may be feasible. A range of TMS concepts is considered here.

It is worth noting that EMAs are not unique in having difficulty with thermal management, although the best method of dealing with the heat is highly dependent on the type of actuator. The Airbus A380 flight test programme showed that additional cooling was required for the aileron EHBAs on that aircraft to enable them to operate in hot (ISA +35°C) environments [6]. This led to a redesign of part of the outboard wing, to increase the airflow around the aileron actuators to provide better convective cooling.

1.2 The Significance of Heat Generation

The two major sources of heat from an electric actuator are the motor(s) and the power electronics within the Electronic Control Unit (ECU). The electric motor is likely to be the most temperature-sensitive of the mechanical components, as gearboxes and ball-screw mechanisms are generally able to operate at high temperatures without severe performance or life reduction [7].

Brushless DC (BDC) and switched reluctance (SR) motors are commonly used motor types for EMAs. Both have the advantage, in terms of thermal management, of small rotor losses [7]. This is important because heat transfer from the rotor is extremely difficult due to the high thermal resistance of the air gap between the rotor and the stationary motor components.

The problems associated with high motor operating temperatures include (from [7]);

1 the resistivity of the copper motor windings increases with temperature, therefore the losses in the windings increase and the motor efficiency is reduced;

2 the reliability of the insulation around the motor windings typically degrades significantly at high temperatures;

3 losses within the magnetic materials of the motor also increase with temperature, which further reduces the overall efficiency.

Both BDC and SR motors require electronic control to govern their speed and rotation direction [1]. The motor speed is controlled by the current supplied by the ECU, which is produced by high-frequency electrical switching using solid state power electronic (SSPE) devices.

All semiconductors generate power losses in the form of heat whenever current is flowing or being switched. The fours major contributions are (from [8]);

1 resistive losses during forward conduction (a function of current through the device and voltage drop);
2 leakage loss when the semiconductor is used to block voltage;
3 switching losses when the semiconductor is turned on and off, which are very small if switching frequency is low but can become large when switching at the high frequencies necessary for motor control;
4 losses in the semiconductor control terminal.

The high currents and switching frequencies necessary for high power electric actuators lead to considerable heat output from the power electronics [1]. Heat loads from the EMA power converter are typically of the same order as the heat loads from the actuator motor [9]. Unless this heat can be dissipated, the resulting temperature rise can permanently damage the temperature-sensitive electronic components, which will disable the motor and cause loss of actuator control [1].

2 Potential Solutions for EMA Thermal Management

Potential solutions and their relative merits are discussed in some detail in [10]. These include direct conduction, air cooled systems and liquid cooled systems. Direct conduction is considered unsuitable due to the difficulties in achieving an adequate thermal path between heat source and sink in an aircraft actuation case.

In terms of air cooled solutions cooling air supply is discussed as well as cool plate technology in [10].

In terms of liquid cooling systems, evaporative cooling is analysed in [10], including heat pipes, thermosyphons, and refrigeration heat pump systems. Thermal energy storage is also discussed in the form of using PCMs to improve peak heat absorption and transfer performance.

2.1 Considerations for TMS Design

Major factors affecting the design of a TMS include; the conditions at the heat source and sink, the selection of an appropriate system concept based on those conditions, as well as practical and operational considerations.

Attention must be given to both the heat source and heat sink; which define the boundary conditions within which the thermal management system is designed [11]. The heat source is characterised by the heat output from the actuators; which is defined by their operating duty cycle [12]. The heat sink selection is influenced by the availability and proximity to the actuator locations. The sink temperature will almost certainly be influenced by the ambient conditions, both in flight and on the ground.

Aircraft structure, skin and the surrounding air are the usual heat sinks for actuators [13], although aircraft fuel, ram air and hydraulic/lubricating oils are also commonly used for other cooling roles. Hydraulic fluid is not available on an AEA; so Schneider [2] suggests that the aircraft structure and skin, and ultimately the ambient air, provides the most feasible heat sink for EMAs as it is available in all control surface actuator locations.

The remote locations of the actuators make a centralised cooling loop difficult to implement, and using such a system would remove some of the installation and maintenance benefits achieved with removal of the hydraulic network [2; 5]. A distributed approach for thermal management is therefore desirable. A passive system (which requires no external power) is also preferable for minimising the overall system cost and aircraft power consumption.

Practical aspects such as hardware size and weight, ease of installation and operating conditions are also important. For instance, the flight control actuators may have to start from a cold-soaked condition and their temperature will rapidly rise once they start operating. This will cause thermal expansion and stress [1]; which means the physical, as well as thermal, properties become important for the materials used for components in contact with the actuators.

3 Case Study Aircraft

3.1 Aircraft Selection

This project evaluated a number of EMA thermal management concepts by applying them to a hypothetical all-electric transport jet; representing a possible successor to the Airbus A320 and Boeing 737. The following paragraphs discuss the reasons underlying this particular choice of aircraft.

The replacement for the A320/B737 will be an enormously important aeroplane for the major aircraft manufacturers and airlines alike; based on the number of these aircraft currently in service and on order, coupled with the rapid growth in air transport predicted for the foreseeable future. Flight International magazine [14] has even described the next generation 150-passenger aeroplane as the "Holy Grail" of upcoming commercial aircraft markets.

3.2 Case Study Assumptions

The general configuration, size and performance (speed, cruise altitude etc.) of the case study aircraft were all assumed to be very similar to those of the current Airbus A320. The location and number of the flight control surfaces and actuators, as well as their functions and redundancy were also assumed to be identical [10]. Although it may be advantageous to configure control surfaces driven by EMAs somewhat differently to control surfaces with hydraulic actuators, optimising the actuator locations and redundancy was beyond the scope of this project. This same approach has been used by industry for similar case studies [15] and enabled existing A320 data to be used for design purposes.

It was initially intended that TMS designs would be made for each of the flight control actuators on the case study aircraft. However, it was soon decided that better use could be made of the available time by designing the different TM systems for only one of the actuators. This would avoid a lot of repetitive design work, which would most likely provide little additional information, and would instead allow a more detailed study to be made for a single actuator. It was assumed that the TMS designs would scale approximately in proportion to the power of the actuator for which they were designed, as the actuator heat output was also assumed to be directly proportional to the power output. Based on this assumption, TMS designs were made for the case study aircraft rudder EMA. As discussed in the next section, the rudder EMA was estimated to be the most powerful of the flight control actuators and therefore represents the biggest challenge for thermal management.

The case study TMS development assumed a "typical" linear EMA design; although to allow some flexibility, no particular baseline actuator was specified. Linear actuators were assumed for all control surfaces, based on the current use of linear hydraulic actuators on the A320. Where it was essential to define the geometry of the heat source(s), the following dimensions were assumed for the heat transfer area of the rudder EMA motor and its power electronics (Fig. 1).

The dimensions shown in Fig. 1 were estimated based on existing EMAs, as shown, with similar power ratings to the rudder EMA (calculated in Chapter 4). The heat was assumed to dissipate only in the radial direction from the motor casing and from a single side of an exposed flat surface to represent the power electronics unit, as illustrated.

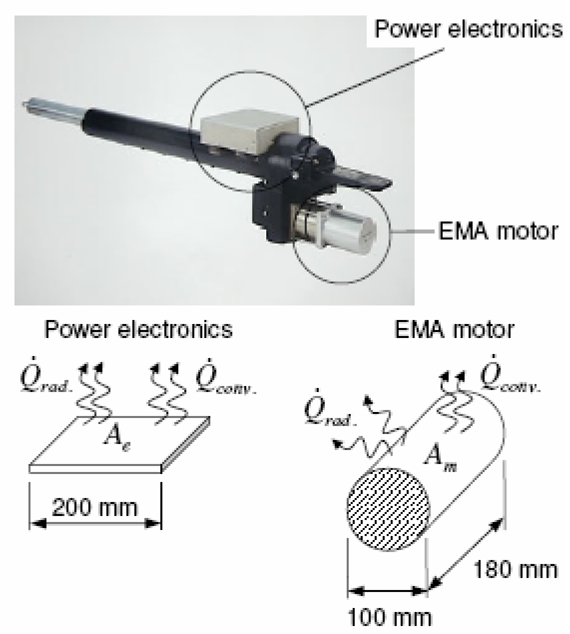

Fig 1. Assumed Heat Transfer Areas.
(Photo from [16])

The design for each of the TM systems assumed a single "worst case" steady-state design scenario, as discussed in Section 4.4. For the design of airworthy thermal management equipment, a large number of flight conditions, including transient conditions and equipment failures, would need to be analysed to determine the critical actuator cooling cases [17].

3.3 Case Study Aircraft Definition

The characteristics below define the aircraft assumed as the basis of the case study; following the assumptions given in Section 3.2. Many of the values are approximate averages across the range of Airbus A320 variants (data from [18]).

Passenger capacity:	150 (nominal)
MTOW:	75,000 kg
OEW:	42,000 kg
Cruise speed:	Mach 0.78
Optimum cruise altitude:	37,000 ft
Maximum altitude:	40,000 ft
Range:	3000 nautical miles
Maximum fuel capacity:	24,000 litres (Jet A-1)
Fuel tank configuration:	Integral main wing tanks & centre wing section tank

Table 1 lists the primary control surfaces and EMAs assumed for the case study aircraft.

Control Surface	No. of Surf-aces	Actuat-ors per Surface	Active per Surface	Active Actuat-ors	Total Actuat-ors
Ailerons	2	2	1	2	4
Primary Spoilers*	8	1	1	8	8
Elevators	2	2	1	2	4
Rudder	1	3	3	3	3
Totals:	**13**			**15**	**19**

Table 1. Case Study Aircraft Primary Control Surfaces and Actuators. ***No. 1 spoilers not included as they only used intermittently on the ground.**

The number, operational use and performance of each of the EMAs on the case study aircraft was assumed to be fundamentally the same as that of the hydraulic flight control actuators onboard the A320 (see Table 2).

	Aileron	Spoiler	Elevator	Rudder
Actuator Stroke (mm)	44	84	60	110
No Load Rate (mm/s)	90	100	60	110
Max. Extend Force (kN)	48.0	44.9	27.7	44.3
Max. Retract Force (kN)	48.0	36.6	27.7	44.3

Table 2. Airbus 320 Actuator Specifications

4 Case Study TMS Design Requirements Derivation

One of the difficulties encountered in designing a heat rejection system for flight control EMAs is defining the design requirements [2]. There are two main elements to be considered:

1. The rate of heat rejection from the EMA and the duration of this heat rejection; which depends on the duty cycle of the actuator. This is affected by the actuator efficiency, control surface attributes and usage, mission profile, air turbulence etc. It is particularly challenging to establish a duty cycle to accurately represent the highly variable control surface usage on a real aircraft. For this reason, advanced FEM modelling and physical testing remain the only practical ways of designing an effective TMS [3].

2. The flight conditions; which define the state of the heat sink. The aircraft altitude and airspeed, ambient air conditions and fuel conditions (volume and temperature) may be important depending on the choice of heat sink.

Collectively, these two factors define the boundary conditions for the heat transfer. How these were defined for the present case study is explained in detail in [10], while the result are summarised in this section.

4.1 Heat Load Estimates

Critical parameters in determining the peak/average heat rejection from an EMA are:

- Peak and average (or "nominal") actuator power consumption
- Actuator duty cycle (which determines the average power)
- Efficiency of the EMA motor and electronic control unit (ECU).

Peak power was taken to be 70% of the product of actuator no-load rate and actuator stall load [10]. This gives the results presented in Table 3 for the case study considered here.

Actuator	Peak Power Output [kW]
Aileron	3.02
Spoiler	3.14
Elevator	1.16
Rudder	3.41

Table 3. Peak Power Estimate for Control Surface Actuators.

Average power was estimated from the 80/20 rule, which has been found to give acceptable approximations [9]. 80/20 rule stipulated that the actuator is at full power 20% of the time and at 20% power the remaining 80% of the time, giving an average power of 36% of peak power. This gives the results presented in Table 4 for the case study considered here.

Actuator	Nominal Power Output [kW]
Aileron	1.09
Spoiler	1.13
Elevator	0.42
Rudder	1.23

Table 4. Average Power Estimate for Control Surface Actuators.

Bland et al. [7] suggest EMA motor efficiencies generally lie in the range of 85-95% and Schneider [19] suggests 90% as a typical value. Similarly, Fronista [12] quotes 93% as the efficiency for the electronics of a prototype aircraft spoiler EMA. For this case study an efficiency of 90% and 93% was assumed for the EMA motor and ECU, respectively. This gives an overall actuator efficiency of 84% ($0.90 \times 0.93 = 0.84$), which agrees well with the recommendations from Lomonova [20] and Simsic [17]; both of whom suggest that an overall EMA efficiency of 85% be used for initial design purposes.

Estimation of the actuator heat rejection can then be made by working back from the known output performance of the control surface actuators. This gives the results presented in Table 5 for the case study considered here.

	Estimated Heat Rejection [W]					
	EMA Motor		Electronics		Total	
Actu-ator	Peak	Nom-inal	Peak	Nom-inal	Peak	Nom-inal
Aileron	336	121	253	91	589	212
Spoiler	349	126	263	95	612	220
Elevator	129	47	97	35	227	82
Rudder	379	136	285	103	664	239

Table 5. Estimated Heat Rejection for Peak and Nominal Operating Conditions

4.2 Energy Storage

Thermal energy storage is an effective method of dealing with large heat outputs during periods at the peak operating condition. The amount of energy to be stored, assuming the basic heat transfer system is sized for the nominal (average) heat load condition, is the product of the difference between the nominal and peak heat rejection rates and the time period over which the peak condition exists. This gives the results presented in Table 6 for the case study considered here.

Actuator	Thermal Energy Storage Requirement [kJ]		
	Due to Motor	Due to ECU	EMA Total
Aileron	64.5	48.6	113
Spoiler	67.1	50.5	118
Elevator	24.8	18.7	44
Rudder	72.8	54.8	128

Table 6. Thermal Energy Storage Requirements

4.3 Operating Temperature Requirements

For power electronics, Sherwani et. al. [21] suggest a typical temperature limit of 120°C at the semiconductor junction. Mohan et. al. [22] recommend a temperature limit of up to 125°C for both electric motors and their power electronics, as thermal coupling usually exists between the two, and also suggest designing for an average temperature at least 20-40°C below the 125°C peak temperature to ensure high component reliability. Based on these values, a maximum operating temperature of 125°C (corresponding to the peak heat rejection condition) and a nominal operating temperature of no more than 80°C (for the nominal heat rejection condition) were targeted for the EMAs in this case study.

A thermal FEM simulation described in [3] for a flight control EMA showed a 10°C temperature drop between the power electronics semiconductor junction and its outer casing. An identical 10°C temperature drop was assumed for this case study. This assumption avoids the need to determine the thermal resistance from the critical EMA components to their respective casings, which would have been impossible for this case study as particular EMA components were not specified.

The effect of designing the TMS for a relaxed maximum temperature limit of 150°C was also investigated in this case study. The purpose of this was to see how much benefit might be derived for the TMS through future improvements in the thermal tolerance of EMA motors and electronics.

4.4 Design Philosophy

Design approaches were considered and the best solution concepts were selected for application to the case study rudder EMA. Based on the requirements reported in this section, potential solutions were down selected [10] to the three most promising, namely; flexible heat pipes, thermosyphons and air-cooled cold plates. The most suitable PCM was found to be acetamide. It is worthwhile here to mention the approach which was adopted for the design of the case study TM systems, based on the requirements discussed in the preceding Sections:

1. For each concept, a "peak" design was made to limit the maximum operating temperature of the EMA to 125°C when it is subjected to the maximum heat load and worst case (e.g. hottest) heat sink condition (assuming no PCM used). The advantage of this approach is that the desired temperature limit of the EMA should never be exceeded, which should ensure it achieves a high level of reliability. The disadvantage is that the TMS may be larger, heavier and more costly than it may need to be, based on the typically short duration of the maximum heat load condition.

2. For each concept, a "nominal" design was also produced based on the nominal temperature limit (80°C); accepting short periods at higher temperatures when the peak heat load condition is encountered (again, no PCM used). This design was then compared with the "peak" design above to determine whether the peak or nominal temperature limit was the more severe constraint. The design corresponding to the more severe condition therefore covers both requirements.

3. A design was also produced for each concept based on the relaxed 150°C temperature limit discussed in the previous Section. The purpose of these designs was to evaluate the impact on the TMS design from possible increases in the allowable operating temperature of future EMA motors and power electronics.

4. Some systems can be designed for the nominal heat rejection, by incorporating a phase-change material (PCM) to store thermal energy during short periods at the peak heat load. This may be a particularly attractive option, provided the thermal storage needs can be met within practical limits, such as using a reasonable mass of thermal storage material. It is important that the PCM temperature under the nominal heat load does not exceed the PCM melting temperature, to ensure that the material will remain solid until the peak heat load is encountered. This approach was used for two of the concepts developed in the case study.

5 Results

Three solutions were designed to the requirements discussed in the previous section.

Each design used consistent materials to ensure a fair comparison, namely; aluminium, copper, distilled water and acetamide.

Details of the three designes are found in [10], and aircraft level results are presented here in Table 7 as a means to compare the three designs based on flexible heat pipes, air-cooled cold plate, and Thermosyphon.

	TMS Mass per EMA [kg]				Total Mass for Aircraft [kg]
	Aileron	Prim-ary Spoiler	Eleva-tor	Rudd-er	
Flexible Heat Pipe					
No PCM	2.84	2.95	1.09	3.20	49.0
No PCM (150°C limit)	2.23	2.32	0.86	2.52	38.5
h fixed at 200 W/m·K	1.79	1.86	0.69	2.01	30.8
Air-Cooled Cold Plate					
PCM	1.89	1.96	0.73	2.13	32.5
No PCM	1.21	1.26	0.46	1.36	20.8
No PCM (150°C limit)	0.93	0.97	0.36	1.05	16.1
Thermosyphon					
PCM	1.99	2.07	0.77	2.25	34.3
No PCM	1.91	1.98	0.73	2.15	32.9
No PCM (150°C limit)	1.85	1.93	0.71	2.09	32.0

Table 7. Aircraft-Level Mass Estimates for Case Study TMS Designs

6 Discussion

6.1 Preferred Thermal Management System

Arriving at a recommendation for the best TMS concept proved challenging for several reasons discussed later in this section. The outcomes of the research and design work carried out during the project are not yet sufficient to enable a robust recommendation to be made, because several areas require further investigation. However, in the absence of a final recommendation, it is useful to summarise the major advantages and disadvantages identified for the case study TMS concepts [10] and to offer a hypothesis as to which concept will be best for the case study aircraft.

It is anticipated that a TMS using ram-air-cooled cold plates will offer the best overall solution. This is based on the following assumptions:

1. It is assumed that the simplicity of the air-cooled cold plate design will result in a relatively low unit cost compared to either heat pipes or thermosyphons. The benefit of low unit cost is amplified on the whole aircraft level, as each aircraft has 19 primary flight control actuators to be cooled.

2. The case study mass estimate suggests the cold plate will give the lightest overall system, even with PCM included in the design; provided the cooling air requirements can be met by small ram air intakes at the actuator locations (which it is assumed would not add significantly to the system mass). Ram air appears to be preferable to an onboard air supply because it is assumed that it would; allow for simpler TMS installation, avoid the need for routing air supply lines through the airframe, and should almost certainly lead to a lighter overall solution. [10] confirmed that the resulting drag penalty is very small.

3. The option of using an acetamide PCM can give a peak temperature reduction of over 40°C (from 125°C to around 81°C) and an improvement in EMA reliability is assumed as a result. This could make the performance of the air-cooled cold plate system superior to a heat pipe system of comparable mass (Table 7).

However, further investigation is required before a final recommendation can be made with a sufficient level of confidence to allow a detailed design study to proceed. Suggestions for areas where future efforts should focus are made in Section 6.3.

6.2 Case Study Design Outcomes

The following conclusions can be drawn from the case study:

The use of a PCM for thermal energy storage does not result in a mass saving for the case study cooling systems. This is due to the specified peak EMA temperature limit (125°C), which is higher than the melting temperature of the PCM (81°C). If the peak operating temperature were comparable to the PCM melting temperature, the PCM may give a reduced system mass; by allowing smaller and lighter components to be designed to transfer the nominal (rather than peak) heat load at the peak temperature.

The selection of the heat sink is possibly the most important design decision for a TMS for flight control EMAs. All the TMS concepts designed for the case study are of similar size and mass and offer comparable performance. The greatest difference between the systems is likely to follow from the choice of cooling air source. The air source selection determines the heat sink (coolant air) conditions, which further determines the heat transfer rate for a given TMS concept and heat source temperature. For the case study designs, the options considered were; convection from the aircraft skin to the ambient air, ram air, and an onboard air supply either from the ECS or recycled cabin air. Convection from the aircraft skin appears to be the best of these because it gives a high cooling air speed and it means no power is consumed in providing the cooling air stream.

The TMS designs produced for the relaxed 150°C peak temperature limit suggest that future improvements in the thermal tolerance of EMA components could potentially allow significantly lighter heat pipes and air-cooled cold plates to be used. The benefit for the thermosyphon would be minimal because its mass is more severely constrained by the EMA geometry and the quantity of working fluid required.

6.3 Recommendations for Future Work

The work carried out during this project has provided useful results by proving the need for thermal management of flight control EMAs and demonstrating the feasibility of three TMS concepts for the case study application. However, further analysis is required before a final recommendation can be made to identify the best of these concepts. Some suggestions are made below for areas to be investigated, as well as how improvements could be made to the work done during this project.

It is expected that the accuracy of the case study work could be significantly improved by using the same design procedures but basing the calculations on defined EMA hardware. If physical testing of the real actuator were possible, the assumptions regarding actuator geometry and heat output could be eliminated as sources of error.

Further work is required to thoroughly investigate the cooling air supply options. This would enable a more complete mass estimate to be produced; which is clearly needed so that the TMS concept mass can be compared on a consistent basis. A trade study is also needed to determine if the EMA reliability improvement from a lower peak operating temperature justifies the mass penalty associated with the use of a PCM.

Detailed design, simulation and testing of hardware will ultimately be required to determine which system offers the best solution for the case study application. Part of this work should include a total system cost estimate; which will be an important factor in the concept selection, as the basic performance of the case study systems appear to be quite similar.

7. Conclusions

The work carried out during this project has proven the need for dedicated thermal management of flight control EMAs and has demonstrated the feasibility of three TMS concepts for the case study aircraft.

Identifying the best concept proved challenging and further work is needed to allow a final recommendation to be made. All three case study TMS concepts are of similar mass and appear to offer comparable baseline performance. However, it is hypothesised that a TMS using ram-air-cooled cold plates will offer the best solution for the case study application; based on preliminary mass, cost and cooling performance considerations.

The use of a PCM for thermal energy storage improves peak cooling performance but does not result in a mass saving for the case study systems. This is due to the mismatch of the 125°C peak EMA temperature requirement and the 81°C acetamide PCM melting temperature. A trade study is needed to determine if the EMA reliability improvement from lower peak operating temperatures justifies the mass penalty associated with the PCM. Future improvements in the thermal tolerance of

EMA components may also mean the TMS designs could be made significantly lighter.

Much of the design work was based on assumptions and only a very small number of assumed flight cases could be considered. This may mean that the case study TMS designs do not accurately represent the hardware that would be required for the case study aircraft. The reliability of the design calculations could also be improved if they were based on well-defined EMA hardware. If physical testing of the actuator were possible, the assumptions regarding actuator geometry and heat output could be eliminated as sources of error.

A thorough investigation of the cooling air supply options is needed to enable a complete mass estimate to be produced. Detailed design and simulation will also be required to ultimately determine which system offers the best thermal management solution for the case study aircraft. Part of this work should include a system-level cost estimate, because cost will be an important factor in the concept selection due to the similar performance of the case study systems.

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