AN INTELLIGENT ICE PROTECTION SYSTEM FOR NEXT GENERATION AIRCRAFT TRAJECTORY OPTIMISATION

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Abstract

This paper describes the development of an Intelligent Ice Protection System (IIPS) for integration into an aircraft trajectory optimisation framework developed as part of the Clean Sky programme. The IIPS is developed in MATLAB incorporating features of more electric systems and future air navigation environment. A typical flight from London Airport Heathrow (EGLL/LHR) airport to Amsterdam Airport Schiphol (EHAM/AMS) was used as a case study. Initial results show that further savings on fuel burn and flight time could be achieved if icing phenomenon is considered in aircraft trajectory optimization scheme.

Nomenclature

m	:	Aircraft mass
V	:	Aerodynamic speed
T	:	Thrust magnitude
h	:	Altitude
L	:	Lift magnitude
D	:	Drag magnitude
g	:	Gravity acceleration
γ	:	Flight path angle
χ	:	Heading angle
c	:	Specific fuel consumption
φ	:	Geodetic latitude
λ	:	Geodetic longitude
R_E	:	Earth radius
μ	:	Bank or roll angle
HP	:	High Pressure
IP	:	Intermediate Pressure
$IIPS$	:	Intelligent Ice Protection System
$R\&D$	:	Research and Development

1 Introduction

The growing trend of air travel has made aviation the fastest growing source of global warming and climate change [1]. Based on the current annual projection of about 5%, the annual passenger total is expected to increase from 3.1 billion in 2013 to 6.4 billion by 2030 [2]. CO_2 emission is by far the largest among pollutants from air transport. In Europe alone, it is estimated that more than 300,000 tonnes of CO_2 is generated from aircraft operations per day [3]. As a result, EU initiated three stream comprehensive projects/measures to mitigate the impacts of aviation on the environment and fuel resources. These are R&D for greener technology, modernised air traffic management systems and market based measures.

The Clean Sky Joint Technology Initiative (JTI) is the flagship of the R&D projects for the greening of air transport in EU. The Clean Sky is a private/public research partnership at European level in the field of aviation to develop the technologies necessary for a clean, innovative and competitive system of air transport. This would be done through the achievement of ACARE targets of reducing the emissions of CO_2, NOx and unburnt hydrocarbons by 50%, 80% and 50% respectively by 2020 referenced to 2000 standard [4]. One of the Clean Sky activities is the Management of Trajectory and Mission (MTM) work package which is under Systems for Green Operations (SGO) - Integrated Technology Demonstrators (ITD).

This research was carried out under the SGO ITD and proposes a controllable ice protection system for aircraft fitted with future air navigation systems. The research aimed at investigating ways to operate aircraft at low power levels through changes in aircraft operation strategy that takes into account optimised flight routings due to icing conditions. Conventional approaches to trajectory optimisation do not take the airframe systems penalty into account in contrast to real aircraft operation. This research has developed a tool capable of sizing and simulating aircraft anti-icing performance for trajectory optimisation which would enable development of decision making processes dependent on weather within the flight management system; thus transforming the conventional Ice Protection System (IPS) to a more intelligent system.

1.1 Objectives of the Research

While continuing to have safety as a primary objective, this work was about utilising future aircraft's Performance-Based Navigation (PBN) concept to investigate possible ways of minimising IPS operational demand power that would lead to greater efficiency and capacity. The primary objectives of this work, therefore, are to:

- develop a consistent and cohesive strategy of managing in-flight icing in a future ATM environment that enables efficient flight planning,
- investigate the response of today's cutting edge aircraft icing technologies in the future 4D navigation environment,
- use optimised aircraft trajectories to investigates ways to operate aircraft at low power levels in icing conditions and
- Conceptualise controllable ice protection system for intelligent aircraft operation.

The secondary objectives are to build IPS model for the total system burden, and algorithm for intelligent operation so that potential savings associated with routing and other operational issues may be explored. This would include assessment of the cost, benefit and risk associated with using routing for aircraft ice protection.

1.2 Performance Based Navigation System

Ground-based systems have served the aviation community well since inception; however as demand for air transportation services increases, they do not permit the flexibility of point-to-point operations required for the future ATM environment [5]. Hence, ICAO has adopted the Performance Based Navigation (PBN) system to address these challenges. PBN defines performance requirements for aircraft navigating on an Air Traffic Service (ATS) route, terminal procedure or in a designated airspace. Through the application of Area Navigation (RNAV) and Required Navigation Performance (RNP) specifications, PBN provides the means for flexible routes and terminal procedures [1]. The International Air Transport Association (IATA) estimated that shorter PBN routes globally could cut CO_2 emissions by 13 million tonnes per year [6]. Flying PBN routes eliminates 3.19 kg of CO_2 emissions for every kg of fuel savings [6]. One of the major advantages of PBN system is that it permits optimal trajectory based operations by providing very precise lateral and vertical flight paths. From 2030 and beyond, aircraft are expected to fly optimal trajectories that are defined in the form of three dimensional waypoints plus associated required times (4D) of overfly [3].

1.3 Concept of Next generation Aircraft

The next generation aircraft is considered to be extremely efficient by design, light weight (composites structures) with lower maintenance and overall operating costs, and reduced impact on the environment. There is a lot of progress towards the development of new and more efficient de-icing systems that are compatible with next generation composite airframe structures. This includes the heater mat technology, smart IPS and icephobic coatings among others. Projects such as Clean Sky, NextGen/SESAR, ON-WINGS, ERAST, Boeing CFD and EADS VoltAir are all projects pursued towards more efficient aircraft systems energy management and cleaner environment.

The next generation aircraft is conceptualised utilising the All-Electric Aircraft (AEA) technology. Though the transition to AEA configuration is still far away, there is a great achievement in a More Electric Aircraft (MEA) technology. In the MEA configuration, it is assumed that the majority of the airframe systems will be powered electrically retaining present form of hydraulic, mechanical or pneumatic power [7] whereas, the AEA concept assumes that the all aircraft systems will be powered electrically.

1.4 Recent Progress in Next Generation IPS

The classical pneumatic anti-icing system typically has a very simple on/off control implementation. It taps bleed air power from the engine which reduces the overall engine performance. This causes high fuel consumption and, CO_2 and NO_x emissions which affects air transport costs and the environment impact along the route. On the other hand, electrical anti/de-icing power could be provided by generators on-board. Goodrich Corp tested electro-thermal technology on a Cessna 303T wing leading edge during the 2003/4 winter, and reported that between 20-50% energy was saved compared to conventional anti-icing system [8]. Boeing 787 is the first large fixed wing aircraft to use electro-thermal de-icing system on aircraft wings. The Boeing 787 power consumption was reduced to 45-75 kW using this technology compared to 150-200 kW needed with classical technology [9]. Another recent technology is the pulse electro-thermal de-icing system developed by Prof. Victor Petrenko [10]. According to Petrenko [11], when a pulse de-icer is fully optimised, only 1% of the energy requirement of a conventional thermal de-icer would be demanded.

Conventional methods of protecting aircraft against inflight icing involve using Active Ice Protection Systems (AIPS). However, AIPS are characterised by complexity and high fuel consumption. Hence, there are on-going research efforts aimed at developing Passive Ice Protection Systems (PIPS) that are easy and require less energy. One prominent feature of PIPS is the use of icephobic coatings on aircraft parts prone to inflight icing to reduce ice adherence to the surfaces.

Previous experiments have shown that icephobic coatings have the potential to significantly reduce power consumption [12]. However, these coatings must have certain chemical and physical properties to withstand aircraft harsh operating environment. Thus, their durability and expected service life have not yet been established so also their overall cost as compared to AIPS. Erosion, corrosion and reaction with atmospheric substances vis-à-vis its effects to the environment are a great challenge to understand at the moment. Response to lightening, electrostatic properties, interference with electromagnetic signals and avionic components are all issues that are not yet resolved [13].

2 Research Approach and Method

There are basically three methods of managing aircraft in-flight icing. These are through development of efficient anti/de-icing systems, effective weather avoidance strategy, and or ice tolerant aircraft designs. In the past, the efforts to reduce air transport cost and its negative impacts on the environment were mainly focused on aircraft and engine designs. While achieving safety, fuel consumption vis-à-vis costs could be minimised through climate compatible operations by better exploiting future real time weather information.

Today, aircraft may deviate from its flight plan only for reasons of safety and weather perturbations. However, due the growing impacts of commercial aviation on the environment and oil resources, smart routings are required to operate aircraft at low power levels to save fuel consumption. Recent advances in intelligent ATM, digital control and computer based automation have provided opportunities to investigate use of optimal flight routes around disturbances which have the potential to decrease safety and increase the environmental impact on aviation.

This approach, which is applicable to all airframe systems, is applied to the aircraft icing problem in this work. In real sense, to achieve autonomous operation in icing conditions, a controllable intelligent ice protection system which enables the development of a decision making process dependent on weather must be integrated into the on-board FMS; thus transforming the conventional IPS into a more intelligent system. The idea is to combine the effect of technology and smart routing in aircraft anti-icing problem as illustrated in **Error! Reference source not found.** Smart routing is an avoidance strategy involving weather-dependent optimized trajectories for efficient and low power levels operations.

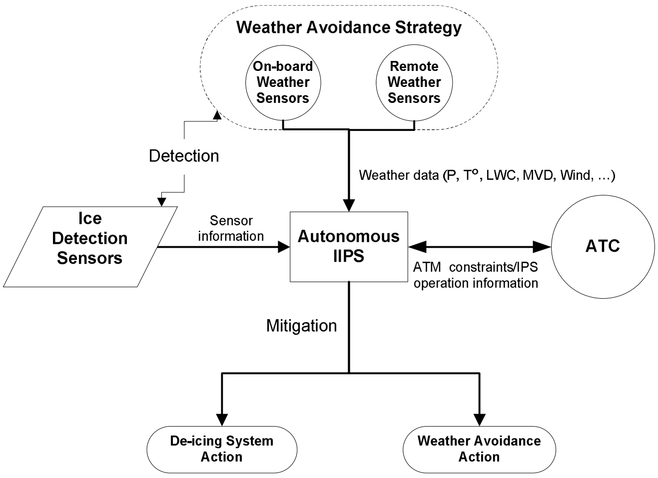

Fig. 1 A Systematic Approach to Controllable Aircraft Anti-icing in Future ATM Systems

In this approach, the IIPS takes only that much power required based on the icing inputs from the sensors or remote weather source. This approach is an improvement on the conventional approach of representing only the aircraft dynamics and engines system; neglecting aircraft systems impacts.

3 Trajectory Optimisation Method

3.1 GATAC Simulation Framework

Greener Aircraft Trajectories under ATM Constraints (GATAC) is a multi-objective optimization framework for planning environmentally efficient trajectories. The software is co-developed between University of Malta and Cranfield University. The University of Malta developed the infrastructure code while Cranfield University developed the optimizer and models.

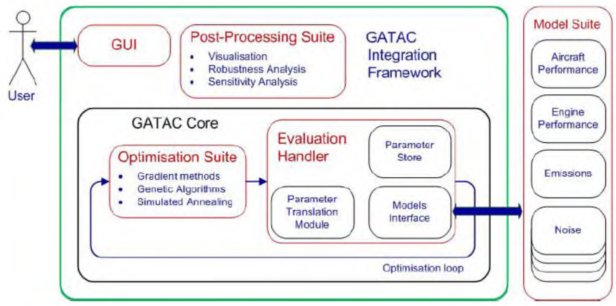

Fig. 2 GATAC Integration Framework Architecture [14]

The current GATAC v3 release allows the user to use four different optimisers to solve trajectory optimization problems. The overall optimisation block diagram of a generic problem using GATAC is shown in Fig. 2. Further reading on GATAC can be obtained in [15].

3.2 Optimiser Choice

The following optimisers are available in GATAC v3:

- Non-dominated Sorting Genetic Algorithm Multi-Objective (NSGAMO)
- Multi-Objective Tabu Search (MOTS)
- Hybrid Optimiser (HYOP)

The NSGAMO optimiser is capable of performing multi-objective optimisation under constraints and is based on Genetic Algorithm (GA). The properties of GA algorithms to optimise problems with local minimums perfectly fit to the needs of this work. A bi-objective optimisation scheme which results in a creation of Pareto front was used to optimise the fuel and time. The theoretical optimal Pareto front solutions are $x_1 \in [0,1], x_j = 0$ where i=2,…,n. The development processes and capabilities of these models and the GATAC simulation framework are discussed below.

4 Models

To enable the simulation of aircraft operation in icing condition, an aircraft dynamics model and major airframe systems models were developed and integrated in the GATAC framework as illustrated in Fig. 3. The framework was developed and validated by using Cranfield models.

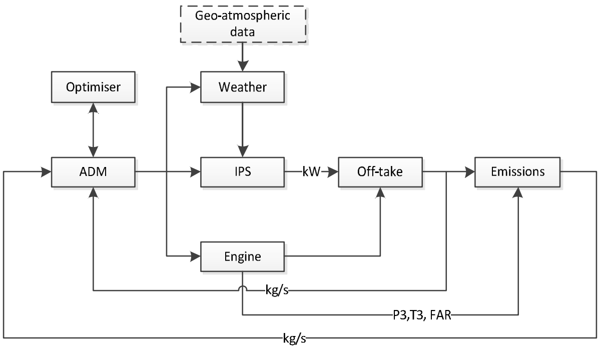

Fig. 3 Models Interface Architecture

The model suite generates a representation of airline operating costs in order to be able to provide a realistic indication of the overall costs associated with the flight time, fuel burn, noise and emissions of the flight mission being optimized.

4.1 Aircraft Model

A representative model similar to Airbus A320 based on EUROCONTROL BADA dataset parameters was used to model aircraft motion. The A320 aircraft was chosen because it is one of the Clean Sky baseline aircraft for technology demonstration. In addition, the A320 aircraft offers advanced navigation technology such as Required Navigation Performance (RNP) capability and Future Air Navigation System (FANS) which are part of the requirements for the use of this methodology. The RNP reduces approach distances for landing while reducing fuel consumption and CO_2 emissions, while FANS optimizes flight path and reduces aircraft spacing. Airbus A320 is an aircraft of the future and therefore suitable for this research.

4.2 Ice Protection System Performance Modelling

The essence of modelling the IPS operation was to estimate the system power requirement under various icing conditions. The IPS is modelled based on the Messinger [16] method utilizes convection, sensible heating, evaporation/sublimation, kinetic energy and viscosity terms in the conservation energy equation to find the equilibrium temperature of an unheated icing surface. Based on this method, the anti/de-icing energy estimated is equal to the energy resulting from the heat balance which includes sensible heating ($\dot{q}_{sensib}$), convective cooling ($\dot{q}_{convec}$) and evaporative cooling ($\dot{q}_{evap}$). However, heat gains due to kinetic energy of the impinging droplets and air must be accounted by the kinetic heating ($\dot{q}_{ke}$) and aerodynamic heating ($\dot{q}_{aero}$) terms, respectively. The anti-icing energy equation is thus given as:

$$\dot{q}_{anti} = \dot{q}_{sensib} + \dot{q}_{convec} + \dot{q}_{evap} - \dot{q}_{ke} - \dot{q}_{aero} \quad (1)$$

$$\dot{q}_{sensib} = \dot{m}.C_{P_{air}}(T_{sk} - T_\infty) \quad (2)$$

$$\dot{q}_{evap} = 0.7 h_0 L_e \left[\frac{R_h e_{surf} - e_\infty}{P_\infty}\right] \quad (3)$$

$$\dot{q}_{ke} = \dot{m}_{local}\frac{v_\infty^2}{2} \quad (4)$$

$$q_{aero} = R_c h_0 \left[\frac{v_\infty^2}{2C_{P_{air}}}\right] \quad (5)$$

Where the local heat transfer coefficient, h_0 is calculated from the following empirical relation:

$$h_0 = Nu.\frac{k_0}{x} \quad (6)$$

The Nusselt (Nu), Prandtl (Pr) and Reynolds (Re) numbers are dimensionless quantities that are calculated from the following relationships:

$$Nu = 0.0296.Re_x^{0.8}.Pr^{0.4} \quad (7)$$

$$Pr = \frac{C_P.\mu}{k_0} \quad (8)$$

$$Re = \frac{\rho_{MSL}.V.l}{\mu} \quad (9)$$

The A320 anti-ice system uses both hot air and electrical heating to protect the critical areas of the aircraft. During flight, hot air from the engine IP and HP bleed ports is used to heat the engine nacelle and, slats 3, 4 and 5. Electrical energy is used instead for de-icing windscreen, probes and waste water drain mast. Summary of the parameters used are shown in Table 2. The model however, is reconfigurable for any medium to large fixed wing aircraft. The anti/de-icing modelling processes were covered in [17]. The electrical power requirement is given in shaft kW and the bleed requirement is given in bleed kg/s; the two of which are connected to the engine offtake model. The difference between this model and the baseline aicraft AI is in the operation. In this model, the IPS algorithm penalises the engine based on icing inputs from sensors/weather data and aircraft mission parameters such as air speed and altitude. In this way, the system demands only the amount of power required for the current operation in contrast to the baseline AI system whereby a fixed value of kg/s and kW are provided for ice protection.

Table 1. Modelling and Simulation Parameters

Parameter	Values	Units
Inputs		
Altitude (*h*)	*User define*	*ft*
Ambient temperature (T_∞)	*User define*	*°C*
Surface heat transfer area (S_0)	*User define*	m^2
Flight speed (V_{TAS})	*User define*	*kt*
Clouds liquid water content (*LWC*)	*User define*	g/m^3
Internal constants		
Mean aerodynamic chord (L_{MAC})	*2.2*	*m*
Slat length (y_{SLAT})	*3.14*	*m*
Leading edge sweep (φ_{LE})	*27.5*	*°*
Skin temperature (T_{sk})	*5*	*°C*
MVD (d_{med})	*20*	*µm*
Pressure (P)	*f(h)*	*hPa*
Saturation pressure (*e*)	*f(T)*	*hPa*
Relative humidity (*Rh*)	*100*	*%*
Specific heat of air ($C_{P_{air}}$)	*1005*	*J/kg.K*
Specific heat of water ($C_{P_{water}}$) @ 0°C	*1859*	*J/kg.K*
Specific density of water (ρ_{water})	*1000*	Kg/m^3
Latent heat for water evaporation (L_e)	*2257*	*kJ/kg*
Latent heat of fusion (L_f) *of ice*	*332.5*	*kJ/kg*
Air density (ρ)	*f(h)*	kg/m^3
Absolute viscosity of air (μ)	$1.5636x10^{-5}$	*kg/s.m*
Thermal conductivity of air (k_0)	*0.0228*	*W/m.K*
Outputs		
Heat flux ($\dot{q}_{anti}$)	*Result*	*kW*
Bleed mass flow rate ($\dot{m}_{bleed}$)	*Result*	*kg/s*

4.2.1 IPS Model Validation

The model performance was evaluated based on an icing experimental test conducted by Al-Khalil et al. [18] on the engine intake of a turbine aircraft. The same test case as the Al-Khalil experiment was run with the model developed in this work and the results compared very well with the experimental result as shown in Fig. 4.

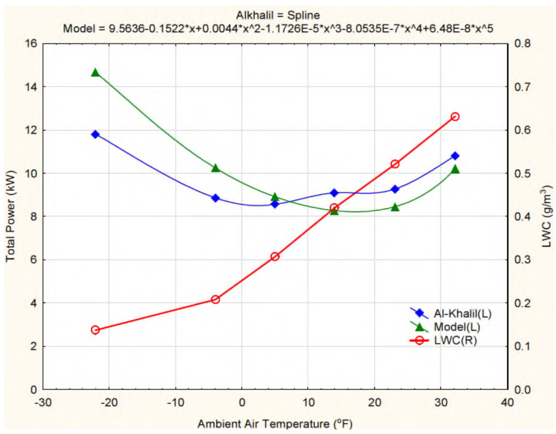

Fig. 4 IPS Model Validation with Experimental Data

The percentage deviation of the model result from the experimental result in terms of total power plotted in Fig. 5 shows less than 20% discrepancies in all the six cases.

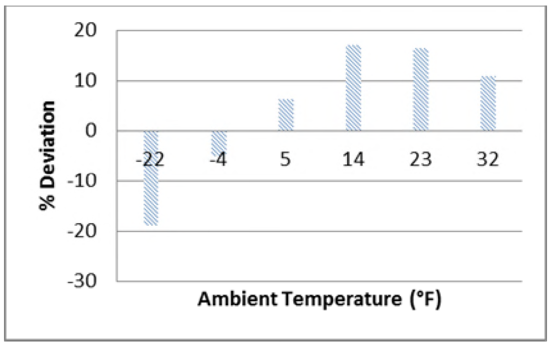

Fig. 5 Percentage Deviation from Experimental Data

Although, there is value in investigating more cases, with the satisfactory sensitivity results and the fact that the range here covers the Appendix C temperature range (0 to -30°C) for the most severe CM icing condition makes the result of the model valid.

4.3 Aircraft Dynamics Model

The Aircraft Dynamics Model (ADM) is an integrated model in GATAC which is in charge of the aircraft trajectory generation of a generic aircraft between two pre-defined positions in a 3D space [19]. The generic aircraft is modelled using the rigid body idealisation with varying mass under aerodynamic, propulsive and gravitational forces with assumption of symmetrical aircraft with thrust force parallel to the motion. In addition the assumptions of spherical, non-rotating Earth and no wind atmosphere are also introduced to simply the problem. The aircraft motion is described by using point mass with three degrees of freedom and the resulting differential algebraic equations are listed below:

$$m\frac{dV}{dt} = T - D - mg\sin(\gamma) \tag{10}$$

$$mV\cos(\gamma)\frac{dX}{dt} = L\sin(\mu) \tag{11}$$

$$mV\frac{d\gamma}{dt} = L\cos(\mu) - mg\cos(\gamma) \tag{12}$$

$$\frac{dm}{dt} = -c\,T \tag{13}$$

$$(R_E + h)\frac{d\varphi}{dt} = V\cos(\gamma)\cos(\chi) \tag{14}$$

$$(R_E + h)\frac{d\lambda}{dt} = V\cos(\gamma)\sin(\chi) \tag{15}$$

$$\frac{dh}{dt} = V\sin(\gamma) \tag{16}$$

The aerodynamic forces are modelled by drag polar characteristic provided by BADA dataset [20] and the gravitational forces are modelled using the International Standard Atmosphere (ISA) datum value (9.81 ms^{-2}). The ADM generated 3D trajectories based on variables provided by the optimiser regarding waypoint positions and altitude and airspeed information along the trajectory. Several input parameters such as initial and final positions and speed and aircraft initial mass are required to support the optimal variable to generate the trajectory and evaluate the overall fuel consumption and flight time, and emission indexes. The optimisation process will evaluate many possible trajectories by varying the trajectory variables previously introduced and refine the search by minimizing the imposed objectives.

4.4 Engine Model

The engine model is based on performance data obtained by Cranfield's in-house developed gas turbine performance code called Turbomatch. The Turbomatch model is similar to the CFM International CFM56-5B4 turbofan engine. The model was validated using EASA [21] and ICAO [22] data. The engine was simulated for a vast envelope of off-design conditions and a performance database was created in Matlab/Simulink. Fig. 6 shows the performance data obtained from the engine model.

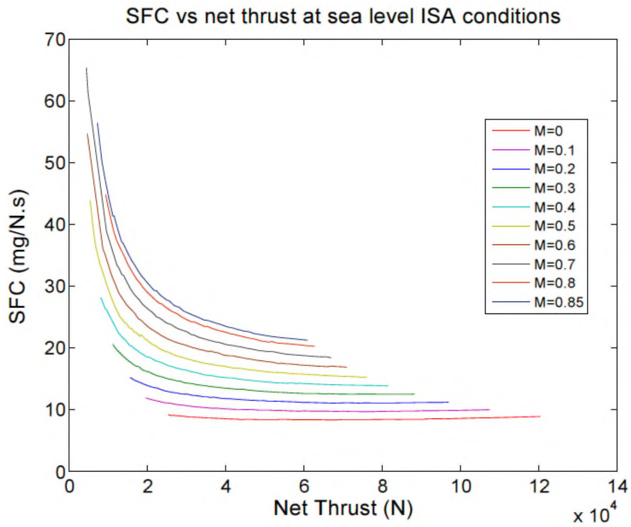

Fig. 6 SFC vs net thrust at SL, ISA

Fig. 7 shows the Simulink model of the engine.

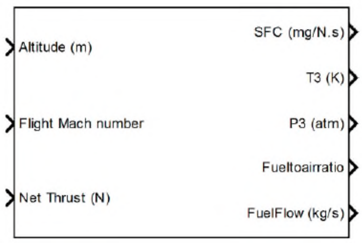

Fig. 7 Turbofan engine Simulink model – Inputs & Outputs

4.5 Off-take Model

In current large commercial aircraft, the secondary power system which includes the IPS is powered from energy extracted from the aircraft engines. As per the nature of the sub-systems the extractions can be divided into bleed air power and shaft power. Typically the bleed air provides power for ECS and IPS. The shaft power extractions from the engines are used to operate the hydraulic pumps which enable the hydraulic system to operate the conventional actuators for the flight controls. Moreover the shaft power extraction from the engines also provides power for the electrical generators mounted on the engines which run the electrics of the aircraft.

The Off-takes model provides the interface between the aircraft systems and the engine. The model is based on the methodology in [23]. The off-takes model takes the fuel flow for an operating condition of the aircraft as an input and then corrects it to represent the penalty due to the operation of aircraft systems. In this case the IPS is operated with bleed air extracted from the HPC of the engine. The model was developed in Matlab/Simulink and shown in Fig. 8.

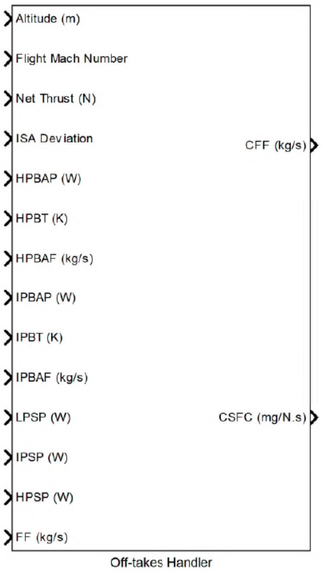

Fig. 8 Off-takes model – Inputs & Outputs

4.6 Emissions Model

The emissions model was based on the P3T3 methodology in SAE International, 2009. It is a correction based method where emissions measurements taken in accordance of ICAO Annex 16 certification engine testing are corrected to required altitude, using combustor operating parameters at both ground level and the required altitude. The baseline emissions indices were extracted from. The model also has the capability to correct the emissions as per the humidity, but for this study the relative humidity was set at 60%. The model was developed in Matlab/Simulink and the schematic with the inputs and outputs as shown in Fig. 9.

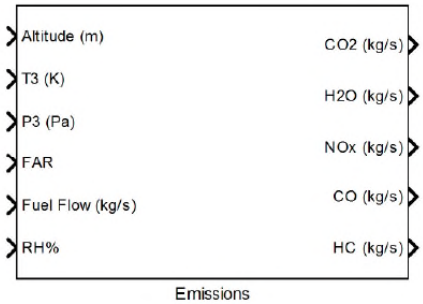

Fig. 9 Emissions model –Inputs & Outputs

Further reading on the emissions model can be found in [24].

5 Discussions and Analysis of Results

5.1 Case Overview

The selected test case is a flight from London Airport Heathrow (EGLL/LHR) to Amsterdam Airport Schiphol (EHAM/AMS). Fig. 10 shows a graphical projection of a typical real flight trajectory obtained from FlightAware, a private flight tracking company [25].

Fig. 10 London – Amsterdam Flight Route [25]

The British Airways and KLM Royal Dutch airlines are the major airlines operating this route. The BA uses A319 and A320 aircraft whereas KLM uses F70 and E190 on this route. This analysis considers an A320 aircraft flying this route in the presence of icing conditions. The degree of protection provided was based on CS25 Appendix C icing envelope shown in Table 2.

Table 2. Appendix C Icing Envelope

Case	T_0 (°C)	LWC (g/m^3)	MVD (μm)	Altitude range (ft)
1	0	0.63	20	0-12000
2	-10	0.43	20	0-17000
3	-20	0.22	20	0-22000
4	-30	0.15	20	0-22000

Typically, aircraft encounters icing during climb to cruise altitude, and descent and hold. This is due the fact that the clouds that contain super-cooled water droplets exist at lower flight levels, and during descent and climb, aircraft reduces speed which lessens the effects of kinetic heating on the airframe. Between 7,000 ft and 13,500 ft during departure and arrival, the algorithm simulates icing condition which automatically puts on the IPS and penalises the engine accordingly.

5.2 Fuel vs Time

Case 3 which represents the most probable icing condition was used for optimising aircraft trajectory with a view to minimising the total fuel consumption and total flight time.

5.2.1 Departure

Fig. 11 shows the Pareto fronts for the conventional method and the enhanced method after optimisation of the departure. The icing in the loop optimisation approach gave a 2.1 % fuel savings over using the conventional method. The two results are quite close with respect to minimum time trajectory. This is expected in the case of a short flight segment like this one.

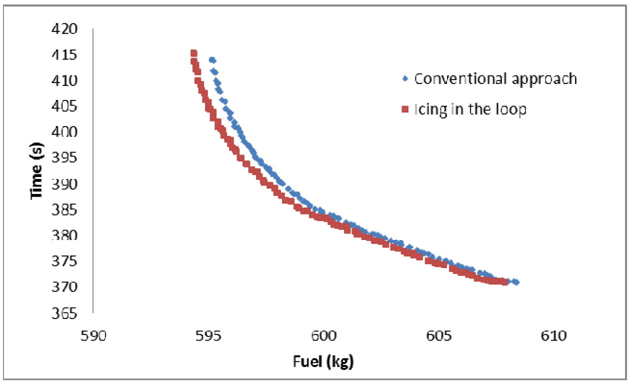

Fig. 11 Difference in Pareto Front between Conventional and Icing in the Loop Approaches

5.2.2 London - Amsterdam Route

The Pareto front for Case 3 for full route optimisation is shown in Fig. 12.

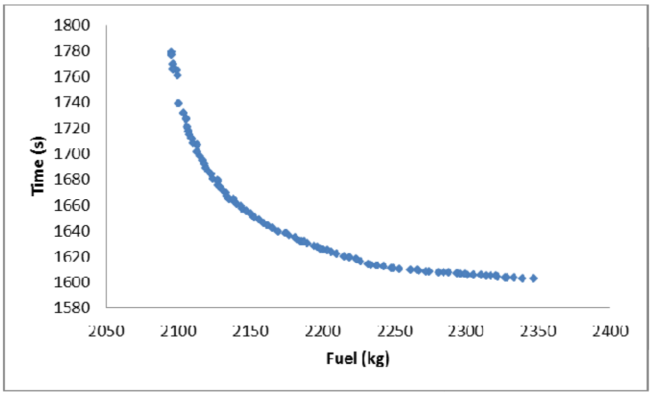

Fig. 12 Pareto Front for London-Amsterdam Route Optimisation

The Pareto shows a difference of 252 kg between the minimum time and minimum fuel trajectories within 3 minutes difference of arrival time. A further simulation was carried out using Case 1 which represents a condition of highest liquid water concentration and the highest icing. The two Pareto fronts are compared in Fig. 13**.** A difference of 66 kg fuel burn was realised between the two cases.

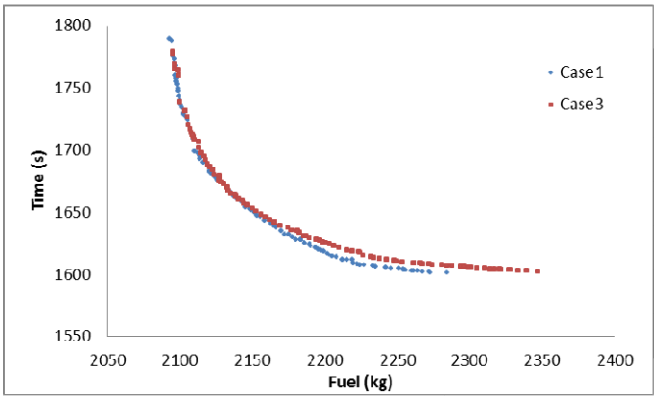

Fig. 13 Pareto Front of Fuel vs Time Simulation

The minimum fuel and minimum time trajectories for Case 3 were compared with a typical trajectory flown by commercial aircraft from EGLL/LHR to Amsterdam Airport Schiphol EHAM/AMS as shown in Fig. 14. The minimum time trajectory was very close to the typical trajectory of commercial aircraft. One of the things learnt from this result is that the typical aircraft finishes climb earlier than the simulated baseline aircraft. This could be associated with ATM operational requirement at LHR.

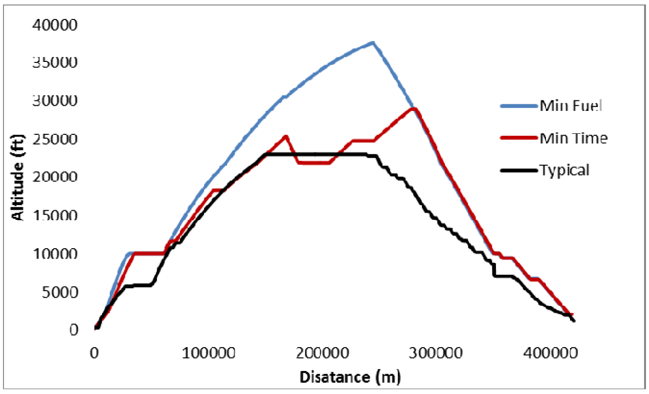

Fig. 14 Trajectory for Min Time and Min Fuel

Fig 17 shows the speed variation with distance. As usual, the minimum fuel trajectory has lower speed profile than minimum time and typical trajectories. Because of this difference in speed profile, the fuel flow requirement was investigated.

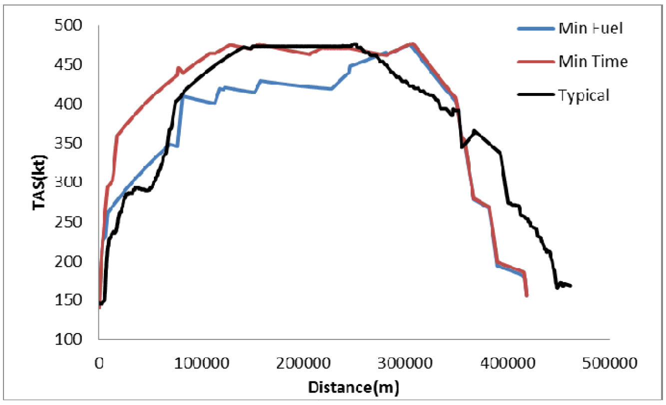

Fig. 15 TAS Comparison

Theoretically, IPS power demand is a function of air speed and altitude. Hence it can be seen that 200 km from LHR, the IPS was autonomously operated with rest to the minimum time trajectory. Fig. 16 shows bleed flow comparison.

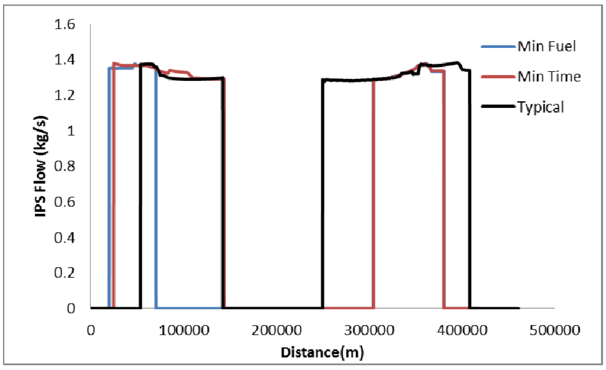

Fig. 16 Bleed Flow due to IPS

Fig. 17 shows the response of the fuel flow to the engine based on the trajectory choice. Although, the initial mass of the aircraft in the typical trajectory is not known, same condition has been applied to it as the study case for ease of comparison.

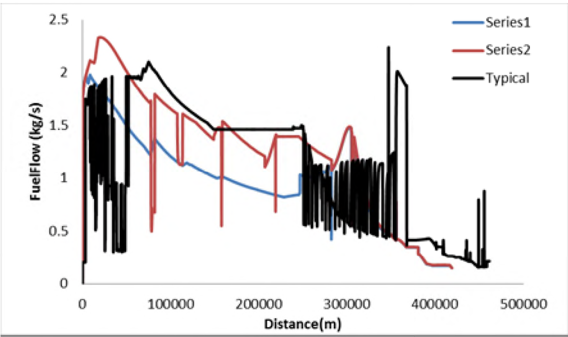

Fig. 17 Fuel Flow vs Distance

The result is as expected with minimum fuel trajectory having lower fuel flow requirement as the minimum time or the low altitude typical trajectory.

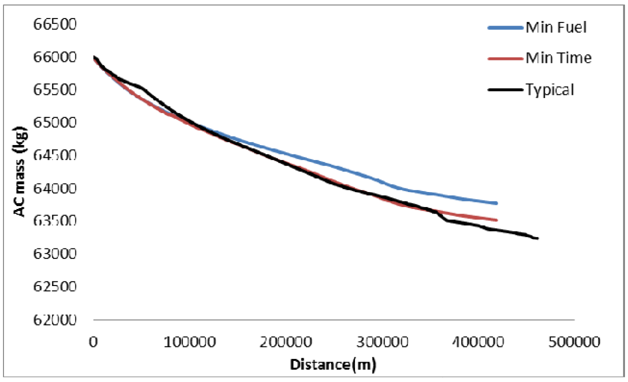

Fig. 18 Fuel Consumption Comparison

In can be noted in Fig. 18 that min fuel trajectory saves more fuel (10.3%) than the typical and min time trajectory. This is because the min time trajectory is achieved through higher TAS as can be seen in Fig. 15. Although the typical trajectory is at similar TAS with the minimum fuel trajectory, it is at a lower altitude where air drag is highest.

6 Summary and Conclusions

This work enabled the development of models and tools contributing to the evaluation of aircraft fuel burn under various environmental conditions. These models and tools enabled a dependable assessment of fuel consumption and pollutant emissions reduction through a mission profile optimization. The models provide quantitative estimates of the energy used by major airframe systems and were part development process for the GATAC (Greener Aircraft Trajectories under ATM Constraints) software.

Although, operation depends solely on the route, operator and aircraft type, it can be noted from the solution of the GATAC trajectory optimization that there are fuel savings and environmental benefits in flying optimized routes in comparison to a typical flight route between LHR to EGLL. Both BA and KLM airlines fly the route between 22,000 ft and 25,000 ft. Meanwhile, the most economic flight profile obtained from the GATAC optimization is a steady climb from LHR to 37,000 ft and cruising for about 5 minutes before gradual descent to EGLL. The persistence of using lower altitudes by the regular operators of the route could be explained considering the minimum time trajectory. ATM constraints are also likely to be a factor.

7 Future Work

Future work involves the integration of the weather model and implementing avoidance strategy in aircraft icing problem. The avoidance strategy is only applicable in a Performance-Based Navigation (PBN) environment. It is therefore based on shared network-enabled information capability. It is designed for future ATM environment where flight operators must have access to current and planned strategies to deal with congestion and other airspace constraints. These constraints might include scheduled times of use for special activity airspace for military, security or space operations. They could also include changes to procedure due to current or forecast weather/congestion as well as the status of area properties and facilities, such as out-of-service navigational aids. In summary, flight operators must continuously obtain up-to-date regular as well as potential ATM limitations, from ground operations to the intended flight trajectory.

In the future work, smart routing techniques will be used to optimize aircraft trajectory in the presence of icing condition. The majority of commercial aircraft nowadays carry an Airborne Weather Radar (AWR) system that is most often built into the aircraft nose. These on-board weather radars provide the pilots with a local weather picture ahead of the aircraft which allows them to identify and avoid specific, undesirable weather formations.

Ice is detected inflight using devices that can detect the presence of ice and send advisory signal to pilot in some cases trigger a de-icing action. Ice detectors can be used in a primary or advisory role. Currently, there are no remote or on-board sensors that can reliably and routinely quantify liquid water content or drop size. At the moment, the AWR system on-board commercial aircraft is used for the detection of thunderstorms, areas of strong precipitation and turbulence only. Some AWR systems have a maximum range of up to 180 nm with 360-degree coverage. However, since precipitation is associated with clouds formation, and clouds and moisture are the main factors for aircraft icing, it can be used in combination with temperature, LWC and droplet size models for predicting and avoiding icing areas.

To achieve autonomous capability, the IIPS must be connected with the FMS whose primary function is the management of the flying aircraft. The FMS using both the GPS and INS to determine the aircraft position can guide the aircraft along a new path safely and conveniently. When icing hazard is detected, two methods are involved in solving the problem. First is to activate the de-icing sequence through electrically powered thermal heating of the critical surfaces; second, to avoid the icing condition by modifying the trajectory to fly in a less severe icing condition. The control law governing the decision process over the efficient operation between the nominal and optimised trajectories is given by:

$$u = [Th, \emptyset, n] \qquad (17)$$

Where Th = thrust, $\emptyset$ = bank angle and n = vertical load factor; all of which are function of time. The thrust component affects the longitudinal motion mainly, whereas $\emptyset$ affects the lateral motion and n affects the vertical motion of the aircraft.

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