Energy and Exergy Mapping of a Modern Aircraft Case Study

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Résumé/Abstract

Cet article présente une approche visant à quantifier l'extraction de puissance des systèmes d'avion dans différentes conditions de vol par l'entremise d'une étude de cas menée sur un avion moderne. Basé sur les derniers travaux dans le domaine de l'analyse énergétique et exégétique dans l'aérospatiale des systèmes pneumatiques, électriques et hydrauliques, cet article chiffre les flux d'énergie et d'exergie au niveau du moteur. Les phases de vol étudiées sont la montée, avec et sans antigivrage, la croisière et l'attente, avec et sans antigivrage. L'extraction de puissance des systèmes en croisière est de 2,5% pour le système pneumatique, 1,5% pour le système électrique et 0,3% pour le système hydraulique. Cet ouvrage vise à établir un étalonnage et à développer une méthodologie de comparaison d'architectures de système d'avions.

This work presents an approach to quantify aircraft systems power consumption in different flight conditions based on a case study of a modern aircraft. Based on recent work in aeronautic energy and exergy analysis of the pneumatic, electric and hydraulic systems, this paper analyses the energy and exergy flows at engine level. The considered flight phases are: climb with and without anti-icing, cruise, and holding with and without anti-icing. The secondary systems power consumption in cruise is divided as follow: 2.5% consumed by the pneumatic system, 1.5% for the electric system and 0.3% for the hydraulic system. This work is intended to be a methodology development and a benchmark to support aircraft system architecture trade studies.

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List of Symbols

A/C	Aircraft	P	Power
c_p	Heat capacity at constant pressure	P	Pressure
CAI	Cowl anti-ice port	R	Specific ideal gas constant
$\dot{E}_n$	Energy flow	s	Entropy
$\dot{E}_x$	Exergy flow, or work potential	T	Temperature
h	Enthalpy	T	Thrust
HP	Compressor high pressure port	u	Fluid velocity
LP	Compressor low pressure port	V	A/C velocity
$\dot{m}$	Mass flow rate		

Background and Introduction

Aircraft and engine manufacturers have been improving aircraft designs and operations since the 1960's where the average fuel burn of new aircraft fell approximately 45% from 1968 to 2014 (Kharina and Rutherford, 2015). However, reductions in average aircraft fuel burn slowed noticeably after 1990 and largely halted around 2000 (Kharina and Rutherford, 2015). The slowed rate of improvement in aircraft fuel efficiency is partly due to manufacturers exhausting conventional technologies and optimizing aircraft and engine designs to maximum feasible levels. An area that has been addressed since the 2000's is improving energy efficiency of secondary power systems, for example by the introduction of more-electric-aircraft technologies (Rosero, 2007). Aircraft secondary power systems transform energy extracted from an aircraft's engines into another form of useful energy to perform their intended functions. In addition, a byproduct of energy transformation in these power consuming systems is energy losses in terms of heat or energy dumped outside of the aircraft.

In parallel, exergy analysis has recently sprouted in the aerospace field since the 2000s (Berg, 2013). While the concept was popularized in the power generation field in the 1970s, exergy was first expressed by Gibbs at the end of the 19th century (Sciubba and Wall, 2007). Exergy is a measure of the quality of the energy. In other words, exergy is the work potential of energy. Mechanical and electrical energies can be fully converted into work whilst heat, chemical and radiation energies cannot without inherent losses.

The purpose of this work is to track aircraft secondary power system consumption in selected flight phases and missions. This energy mapping exercise would help visualize and determine areas where possible efficiencies improvements should be targeted on future aircraft efficiency programs.

Methodology

The analysed A/C system's architecture is conventional. The secondary power systems are namely the pneumatic, hydraulic and electric systems. Figure 1 shows the systems energy & exergy tree at engine level. Additionally, the power source of each system at engine interface is shown in Table 1. It is considered that the systems are only powered by the component identified in Table 1. No power exchange between systems is considered. Note that the case study is based on simulation data rather than actual flight data.

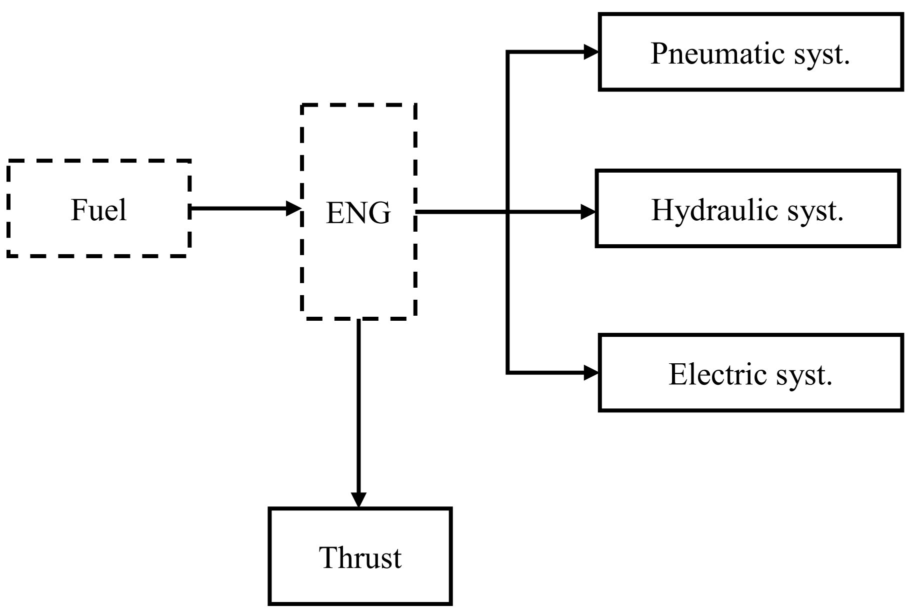

Figure 1. Engine level energy tree, full borders indicate the studied energy and exergy flows

Table 1. Systems power extraction at engine interface

System	Electric	Hydraulic	Pneumatic
Power source	Variable Frequency Generator	Engine driven pump	Engine bleed including fan flow, LP, CAI, HP

Computing Exergy

Mechanical and electrical exergy flows have the same value as its energy flow. However, fluid flow energy cannot be fully transformed in useful work. The generic form of energy and exergy for a given fluid flow are given in equations (1) and (2) (Berg, 2013). Equation (3) is built on (1), neglecting the potential and kinetic energy. Furthermore, the flow enthalpy is expressed based on flow parameters. Equation (4) is built using equation (2), neglecting potential and kinetic exergy. Entropy of equation (4) is expressed based on flow parameters.

$$\dot{E}_n = \dot{m}\left((h - h_o) + \frac{u^2 - {u_o}^2}{2} + g(z - z_o)\right) \quad (1)$$

$$\dot{E}_x = \dot{m}\left((h - h_o) - T_o(s - s_o) + \frac{u^2 - {u_o}^2}{2} + g(z - z_o)\right) \quad (2)$$

$$\dot{E}_n \approx \dot{m}\left(c_p T - c_{po} T_o\right) \quad (3)$$

$$\dot{E}_x \approx \dot{E}_n - \dot{m} T_o \left(c_p \ln\frac{T}{T_o} - R \ln\frac{P}{P_o}\right) \quad (4)$$

In equations (1) to (4), the subscript “o” refers to the reference state used for the computation. As one deduces, the reference states has a direct impact on exergy flow. Berg, (Berg, 2013), demonstrated that the most representative reference state is aircraft-fixed, i.e. stagnation pressure and temperature of air should be used. The reference states used through this case study are the ISA conditions at corresponding altitude.

Systems energy & exergy computation

Energy and exergy computation of the pneumatic system extractions are based on equations (3) & (4) respectively. The hydraulic system is powered by pumps mounted on the engine accessory gearbox. Since the power extraction is done through a mechanical link, hydraulic energy and exergy power offtakes are equal. The electric system is powered by engine driven generators also installed on the engine's gearbox. As for the flight power, it is defined as the product of thrust and true airspeed, as per equation (5).

$$P_{flight} = T \cdot V \tag{5}$$

Flight phases

The flight phases considered in this case study are shown in Table 2. In cruise, the climb and leveled acceleration performed are neglected since their durations are bellow a few minutes.

Table 2. Mission and flight phases to be studied

Flight phase	Design mission	Icing mission
Climb	X	X
Cruise	X	
Holding	X	X

Results

The system's energy and exergy consumption per mission and flight phases are shown in Table 3 & Table 4 respectively. Little difference is observed between the two analyses since only the pneumatic exergy flow differs from its corresponding energy flow. As for the secondary systems power extraction in design mission, it represents 3% to 8% of the engine power output. In contrast, the pneumatic system consumption is 5 to 8 times more energy in the anti-icing mission than its design mission counterpart.

Table 3. Energy systems consumption per flight phase

Flight phase	Alt (ft)	Power consumption (%)			
		Pneumatic	Electric	Hydraulic	Flight
Anti-icing OFF					
Climb	25,000	1.8	0.7	0.3	97.2
Cruise	45,000	2.5	1.5	0.3	95.8
Holding	16,900	4.6	2.8	0.5	92.0
Anti-icing ON					
Climb	25,000	8.9	0.6	0.2	90.2
Holding	16,900	37.2	1.9	0.3	60.6

Table 4. Exergy systems consumption per flight phase

Flight phase	Alt (ft)	Power consumption (%)			
		Pneumatic	Electric	Hydraulic	Flight
Anti-icing OFF					
Climb	25,000	1.7	0.7	0.3	97.3
Cruise	45,000	2.3	1.4	0.2	96.0
Holding	16,900	4.3	2.8	0.5	92.4
Anti-icing ON					
Climb	25,000	8.3	0.7	0.2	90.8
Holding	16,900	35.5	1.9	0.3	62.3

Analysis

Table 3 highlights that the energy consumption of the secondary systems in cruise represents 4.3% of the engine power production, where the pneumatic system is the highest consumer with more than half of the power extraction. Consequently, the engine power output could be reduced by 1% assuming a new architecture or a new technology could halve the pneumatic power consumption. Therefore, optimizing the pneumatic system consumption cruise could lead to significant fuel saving for long range aircrafts.

Additionally, Table 3 shows that in holding with anti-icing on, the secondary systems power consumption reaches 39.5% of engine power, where the pneumatic system is the highest consumer. In the studied aircraft, wing anti-icing is realized by blowing hot air in the wing leading edge. Reducing the pneumatic power consumption in this flight condition could lead to overall power savings. First, alleviating this critical point of the pneumatic system design envelope would reduce both its size and consumption. Second, reducing the holding power consumption results in a reduction of the reserve fuel carried at each flight.

Finally, the differences between the results of Table 3 & Table 4 are within 2% with anti-icing on and within 0.1% with anti-icing off. This behavior is a consequence of the electric, hydraulic and flight energy and exergy flows being equals while only the pneumatic system exergy is different than its energy.

Conclusion

The purpose of this work was to establish a methodology for aircraft energy usage analysis and perform a benchmark of secondary systems energy consumption on a modern aircraft.

The established methodology is based on recent work in energy and exergy application on aircraft transport and uses theoretical data to predict energy and exergy usage of the studied aircraft configuration. This methodology is a tool to compare energy usage between aircraft system architectures in order to improve trade study processes and take more informed decisions.

The studied benchmarking case was analyzed on its design mission, and the results showed that secondary power systems consume 4.3% of the available engine power in cruise devised as follows in cruise: pneumatic power 2.3%, electric power 1.4%, and hydraulic power 0.2%.
It is also worthy to note that in a holding condition, with anti-icing on, the bleed system consumes 37.2% of useful power.

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