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A Synthetic Optimization of More-Electric Aircraft Based on Exergy Analysis

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Abstract:

In order to improve energy efficiency of more-electric aircraft, not only the fuel efficiency, but also the electric efficiency should be developed, since more electric consumers are implanted into the vehicle. Exergy is a powerful method to analyze various physics-based subsystems into one physical scale. This paper uses Exergy Analysis (EA) method to model a more electric aircraft with propulsion, ECU, anti–ice, electricity generating and distributing, electric motors, and airframe. In a classic cruising mission profile, the energy consumption situations of each subsystem and between subsystems are identified respectively. Then an exergy-based synthetic optimization is performed, utilizing Genetic Algorithms (GA) to get global optimal design variables resulting in high energy efficiency of the entire system. The method mentioned in this paper could also be used in other kinds of vehicles.

Keywords:

Exergy Analysis, more-electric aircraft, Genetic Algorithms, energy management.

1. Introduction

The new generation of aircraft rely heavily on electrical power since the widely use of electrical components and electronic flight instrument systems. Therefore, the analysis and optimization method of aircraft performance characteristic should also follow the new trend. As an alternative to mathematical optimization, an exergy-based synthetic design analysis approach can be used [1]. Such an approach can improve the existing analysis and optimization methods by, for example, relating every system component and subsystem to the overall system requirements in a framework of common metrics. Exergy analysis could be used as a potential method for aircraft system synthetic design analysis and optimization. The advantages of exergy-based methods come from their ability to support all required levels of synthetic design activity in a unified fashion aiding the search for system-level, optimized synthetic designs.

Many research have been produced for applications of exergy analysis and optimization for aircraft subsystem design and operation. Butt [2] presented detailed results of the application of energy- and exergy-based methods for the integrated synthesis/design and optimization of an Air-to-Air Fighter (AAF) aircraft with and without wing-morphing capability. The objective functions he used consisted of an airframe subsystem and propulsion subsystem. The result showed that the morphing-wing AAF syntheses/designs outperform those for the fixed-wing aircraft in terms of exergy destroyed/lost and fuel consumed. de Oliveira and his team et al. [3] used the Exergy Analysis (EA) as a method to analyze turbofan as well as fuel consumption of more electric aircraft subsystems, including more-electric engine. Tona et al. [4] used EA to analyze a turbofan in a typical commercial flight. For the global analysis, two reference systems were proposed: one fixed on the ground and the other attached to the engine. The overall engine performance was evaluated over a complete flight mission. Finally, cruise phase costs the highest total exergy though it has higher exergy efficiency. A local exergy analysis showed the distribution of irreversibilities among the engine equipment, defining the most inefficient components are the combustion chamber and the mixer, which are responsible for 50-66% of the total destroyed exergy. Gandolfi et al. [5] used

EA to describe a more electric conventional commercial aircraft with electrical subsystems of electric control surface actuators, cabin compressors for the air conditioning and electric heaters for the ice protection system. The results showed the main source of irreversibilities during a complete mission is the engine with 99% of the total exergy destruction, mainly because of the elimination of the bleed system and substitution for more electric systems. Berg et.al. [6] presented a software tool prototype to allow the management of an aircraft exergy map. An unmanned aerial vehicle system was presented as a simple case study, which allowed the representation of mass and aerodynamics in such an analysis to be discussed. A turbojet study isolated the reference state problem and illustrates the need to use a moving, aircraft-fixed reference state.

In this paper, to analyze the energy loss of a more electric aircraft many subsystems are concerned: the subsystems of propulsion, airframe, an anti-ice subsystem and an ECU. Furthermore the entire vehicle is exergy-based evaluated over a normal cruising mission constructed by seven phases. So each subsystem/component's destroyed exergy can be illustrated in every flight phase. Finally, the analysis results are used to synthetically improve the original design by GA, obtaining the minimum irreversible energy loss of the aircraft.

2. Model

2.1. Mission Profile

The aircraft operation condition will be estimated in a normal cruising mission shown in table 1, which includes: 2 minutes taking-off, 10 minutes climbing from 0 to 11km, short cruising for 8 minutes, higher cruising on 13km for 40 minutes, 8 minutes descending to 4.5km and loiter for 20 minutes, and landing for 6 minutes.

Table 1. Mission Profile

Phase	Height (km)	Ma	Duration (min)	Ambient Temperature (^{o}C)	Ambient Pressure (MPa)	Sonic Speed (m/s)
1 Taking-Off	0	0.2	2	15	1	340.29
2 Climb	6	0.57	10	-24	0.47	316.45
3 Cruise	11	0.77	8	-56.4	0.23	295.15
4 High Level Cruise	13	0.77	40	-56.5	0.17	295.07
5 Descending	10.7	0.62	8	-54.4	0.24	296.47
6 Loiter	4.5	0.4	20	-14.2	0.58	322.57
7 Landing	0	0.2	6	15	1	340.29

2.2. Subsystem models

The propulsion subsystem is regarded as the major consumer of energy in the vehicle (more than 90%). Though respectively small, the irreversible consumption of other subsystem could also be important indices when making decisions, and also could give a hand of consuming energy.

This paper mainly concerns about the following subsystems: propulsion, ECU, anti–ice, electricity generating and distributing, electric motor as well as airframe.

Each subsystem could be expressed by the exergy balance relationship, which is: the input exergy equals to the sum of output exergy and consumed one. It is simple to depict the energy flows between each subsystem by this method though aircraft’s system is a highly complex. Here, the balance equations are expressed by the differential of time, which are time independent. Exergy is denoted by *Ex*; electric exergy which equals to the electric power is denoted by *W*; mechanical exergy is denoted by M, which equals the mechanical power. For the model, energy flows are shown as follows,

$$\dot{Ex}_{des\_propulsion} = \dot{Ex}_{fuel} + \dot{Ex}_{air} - \frac{d(V\cdot T_{thrust})}{dt} - \dot{W}_{shaft} \tag{1}$$

$$\dot{Ex}_{des\_electric} = \dot{W}_{electric} - \dot{W}_{motor} - \dot{W}_{ice} - \dot{W}_{ECU} \tag{2}$$

$$\dot{Ex}_{des\_ECU} = \dot{W}_{ECU} + \dot{Ex}_{ECU\_Inlet} - \dot{Ex}_{ECU\_Outlet} \tag{3}$$

$$\dot{Ex}_{des\_motor} = \sum_{i}^{n} \dot{W}_{motor\_i} \tag{4}$$

$$\dot{W}_{ice} = \dot{Ex}_{des\_ice} = An\cdot S_{ice}\cdot T_{ice}(1-\frac{T_0}{T_{ice}}) \tag{5}$$

Equation (1) is the destroyed exergy of propulsion subsystem $Ex_{des\_propulsion}$. This subsystem provides the thrust force T_{thrust} to maintain the flight vehicle at a certain level in a certain speed V, as well as the motivation power to the generator. The difference between input and output exergy is irreversible. The exergy which goes into the subsystem contains of the fuel exergy Ex_{fuel} and the air exergy Ex_{air}, calculated respectively by equation (6) and (7).

$$\dot{Ex}_{air} = \dot{m}_{air}[C_p(T - T_0 - T_0 \ln\frac{T}{T_0}) + R\cdot T_0\cdot \ln\frac{p}{p_0} + \frac{V^2}{2}] \tag{6}$$

where, $\dot{m}_{air}$ is the air mass flow rate; C_p is the specific heat capacity of air; T is the temperature of air; R is the ideal gas coefficient; p is the pressure; V is the velocity of the air. The subtitle 0 is the ambient condition.

$$Ex_{fuel} = \dot{m}_{fuel}\cdot\{C_{pf}[(T_b - T_h) - T_0 \ln\frac{T_b}{T_h}] + R\cdot T_0 \ln(\frac{p_b}{p_h}) + \dot{Ex}_c\} \tag{7}$$

where, $\dot{m}_{fuel}$ is the fuel mass flow rate; C_{pf} is the specific heat capacity of fuel; Ex_c is the chemistry exergy contained by the fuel. Also, the subtitle b represents the burning condition; the subtitle h represents the fuel condition just before it flows into the combustor.

In general, the power used for generating is decided by the total power of electric consumers. Here, it is assumed that the output shaft power of the engine without load W_{shaft} totally transforms into electricity $W_{electric}$. The value will reduce in real electrical loads condition. The electric power is allocated to actuation, anti-ice and ECU system, illustrating by equation (2).

In this more-electric aircraft, the anti-ice subsystem presented by the subtitle of ice, is designed electric heated. In equation (5), An is the heat transfer coefficient of the heating surface; S_{ice} is the heating surface area which is proportional to the reference surface S, and there is a constant $0<k_{ice}<1$, such that $S_{ice} = k_{ice}S$.

The ECU subsystem is in charge of the temperature and the pressure level in the cabin. Destroyed energy process which happens in this subsystem is complex, including the structure heat dissipation, radiating, and human metabolism. We only focus on the affection of the air, denoted by equation (3).

Not all of the electric motors should work during the whole mission. For simplification, the energy consumption of motors Ex_{des_motor} in equation (4) is averagely allocated into each mission.

2.3. Airframe exergy model

Referring to the airframe, since almost all of the irreversible exergy loss comes from the friction in the subsonic situation. This research mainly cares about the exergy consumption caused by friction. The equation is as follows [2]:

$$\dot{E}x_{des,drag} = \frac{T_d D V}{T_0} \tag{8}$$

where, D is the drag which contains two parts, lift reduced and zero lift.. The wing loading is used to express the drag coefficient. So the equation (8) turns into the expression as follows,

$$\dot{E}x_{des,Airframe} = \frac{T_d V}{T_0} \cdot \frac{q}{\frac{W_{TO}}{S}} [\frac{n^2}{q^2 \pi A e} (\frac{W_{TO}}{S})^2 + C_{D0}] \cdot W_{TO} \tag{9}$$

where A is the aspect ratio of the wing; e is oswald's efficiency factor; n is overload; T_d is the "dead state" temperature used in the exergy calculations; q is the dynamic pressure; W_{TO}/S is the take-off wing loading; C_{D0} is the zero lift drag coefficient.

2.4. Parameters

The parameters used in the evaluation are as follows,

Table 2. Parameters of subsystems

ITEMS	*UNITS*	*VALUES*
Cabin temperature T_{cabin}	K	294.25
Cabin pressure P_{cabin}	kPa	75.3
Take-off weight W_{to}	kg	11342.7
Thrust in sea level T_{SL}	kN	205.9212
Overload n	-	5
Zero lift drag coefficient C_{D0}	-	0.0035
Wet area ratio R_{wet}	-	2.9

3. Optimization

3.1. Objective function

The system-level optimization problem is based on the total amount of exergy consumption over the entire mission and the objectives are defined as follows. The subsystems of propulsion, ECU, anti-ice, and actuation are mainly concerned when evaluating the consumption.

Min

$$Ex_{des} = Ex_{des,PS} + Ex_{des,Airframe} + Ex_{des,anti-ice} + Ex_{des,ECU} + Ex_{des,motor} \tag{10}$$

Since some of the variables of airframe are also related to the exergy computation of propulsion and anti-ice subsystem, they should be the global optimal variables. For instance, the aspect ratio and the wing loading are both function of the reference surface S, which is proportional to the exergy consumption of the anti-ice subsystem as mentioned in equation (5). Therefore, the aspect ratio A, the wing loading W_{TO}/S and the anti-ice temperature T_{ic} should be optimized together. Similarly, there is a relationship between the thrust and the wing loading which is illustrated later in section 3.2.4. Therefore, the fuel temperature, the inlet temperature, the air mass flow and the fuel mass flow which are decision variables of thrust calculation should also be global optimized. All the optimal variables are as follows,

w.r.t

$$\{ A , W_{to}/S , T_f , T_{ic} , T_{inl} , \dot{m}_f , \dot{m}_a , \dot{m}_{inl} , \dot{m}_{cb} \}$$

3.2. Constraints

3.2.1. Positive entropy generation

Since the entropy generation must be positive, the lost exergy should also always be positive, despite the system is a power producer or a power user.

$$ex_{des,PS} \geq 0, \quad ex_{des,Af} \geq 0, \; ex_{des,ECU} \geq 0, \; ex_{des,M} \geq 0$$

3.2.2. Steady level flight

When the aircraft is in unaccelerated level flight, this leads to the sum of the forces equal zero.

$$T = D = qS\left(C_{D,0} + KC_L^2\right) \tag{11}$$

$$L = W = qSC_L \tag{12}$$

where, K is the induced factor.

3.2.3. Engine thrust characteristics estimation formula

The thrust provided by turbofan could be evaluated in the form of the thrust in the static state at sea level, which is expressed in equations below.

$$T = T_{SL}K_{M1} \cdot PT_S \cdot PT_T \tag{13}$$

$$PT_T = \left(1 + b_T M^2\right)^{X_{PT}} \tag{14}$$

$$K_{M1} = \begin{cases} 1 - b_1\left(1 - M\right) & M \leq 1.0 \\ 1.0 & M > 1.0 \end{cases} \tag{15}$$

$$PT_S = \begin{cases} 1 - H \times 2.2558 \times 10^{-5} & H \leq 11000m \\ 0.276e^{-(H-11000)/6341.6} & 11000m < H \leq 20000m \end{cases} \tag{16}$$

where, T_{SL} is the static thrust at sea level without afterburner; PT_S is the static pressure and temperature correction factor in current flight level; PT_T is the total pressure and temperature correction factor of velocity variation; b_1 is the correction factor which equals to 0.2 with afterburner and 0.3 with maximum thrust offering; M is the mach number; H is the flight level.

3.2.4. Energy conservation law

According to the energy conservation law, as well as the expression of drag, the design space of thrust-to-weight ratio and wing loading is expressed as follows,

$$\frac{T_{SL}}{W_{TO}}=\frac{\beta}{\alpha}\{\frac{qS}{\beta\cdot W_{TO}}[\frac{An^2\beta^2}{q^2}(\frac{W_{TO}}{S})^2+C_{D0}]+\frac{1}{V}\frac{d}{dt}(H+\frac{V^2}{2g})\} \quad (17)$$

where, β is the weight factor, aircraft weight $W=\beta W_{TO}$, and $\beta<1$; α is the thrust lapse term, illustrating the relationship between T_{TO} and T_{SL}. In a former work, the weight factor β of each flight mission is iteratively computed. Thus, the design space according to the whole mission is shown in figure 1.

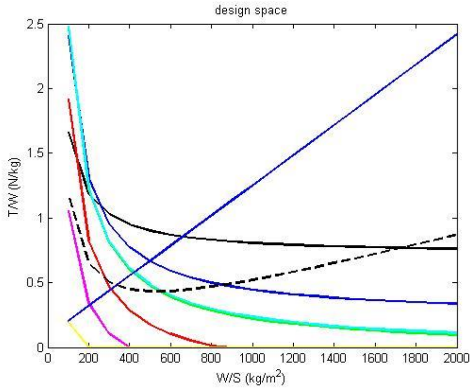


Fig. 1. Design space according to the relationship between T/W and W/S.

3.3. Genetic algorithm

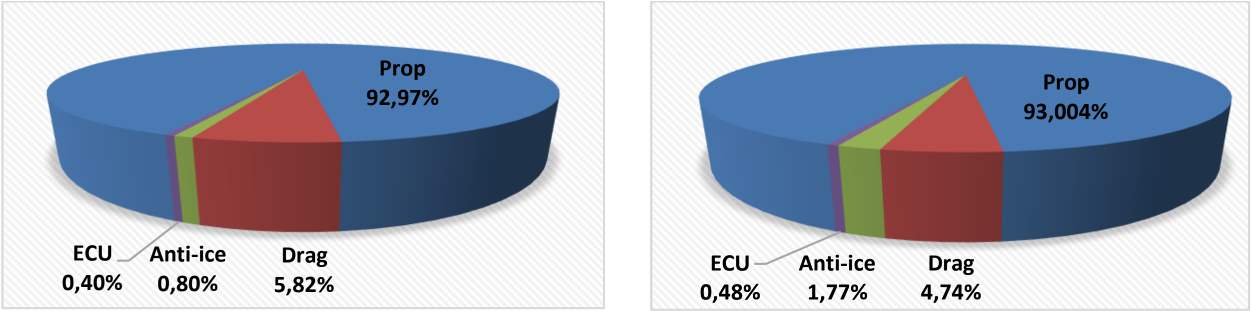
In this optimization, the Stochastic Universal Sampling method is chosen as the selection function. The mutation function is real-value mutation like Breeder Genetic Algorithm, which mutates the individuals with probability depending on the number of decision variables. In addition, the boundaries of each variable are illustrated in table 3.

Table 3. Variable ranges for optimization

ITEMS	RANGES
$\dot{m}_a$	$650<\dot{m}_{air}<900$
$\dot{m}_f$	$0.5<\dot{m}_{fuel}<5$
A	$1.8<A<8$
W_{to}/S	$100<W_{to}/S<1000$
T_f	$270<T_f<300$
T_{ic}	$216.65<T_{ic}<350$
T_{inl}	$216.65<T_{inl}<350$
$\dot{m}_{inl}$	$0.05<\dot{m}_{inl}<10$
$\dot{m}_{cb}$	$0.05<\dot{m}_{cb}<10$

4. Results and analysis

In figure 2, energy consumption of the global system in cruise and descending phases is shown in sub-figure (a) and (b) separately. Obviously, the propulsion subsystem contributes the majority of irreversible energy loss in both phases, resulting in 93%. Drag consumes the second large of 5.8% exergy in cruise phase and 4.74% in descending phase; ECU and anti-ice subsystem costs less than 1% of global energy in cruise phase, respectively.



(a) Phase of cruise *(b)Phase of descending*

Fig. 2. Proportion of exergy consumption in different flight phases

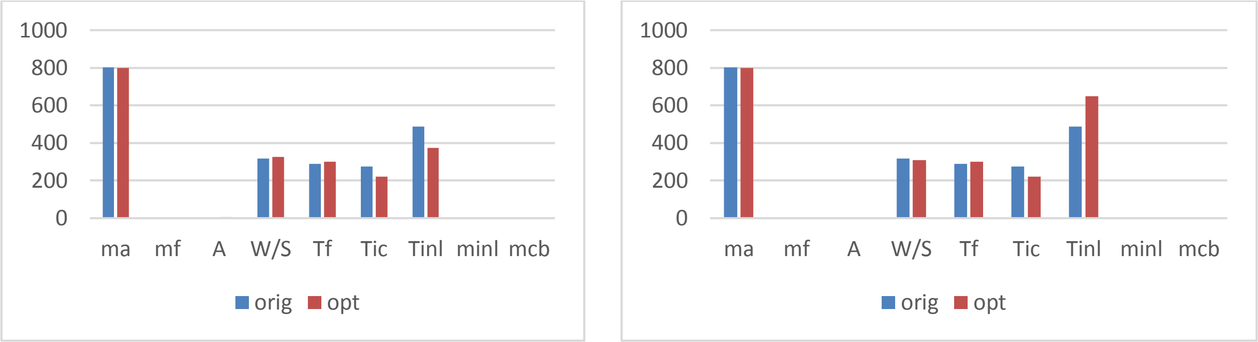
In addition, one of the optimization results of cruise phase is shown in table 4. The original values used in this optimization are calculated by the methods in [7]. The W_{TO}/S is the optimized value considering of take-off, overload and stalled limitation. The W_{TO}/S increases to 324.6, which means that in order to consume less exergy, the reference surface S should decrease since the take-off weight is assumed to be constant. On the other hand, one should notice that while reducing the S the aspect ratio A raises from 2.19 to 4.3. The root of the wing should be 4 times longer than the tip, at the same time the wingspan should be shorter. Referring to the input fuel temperature T_f, while maintaining inside the design space, the optimal result shows that a pre-warm to 300K saves the destruction of fuel exergy. There are little changes in the air and the fuel mass flow, in global optimization, 0.48% reduction and 1.08% growth respectively. The anti-ice temperature is much lower than the original value since its lower limit is the ambient temperature at the certain level but not 0^oC.

Table 4. Optimization results of variables in cruise phase

ITEMS	Original value	Optimal value
$\dot{m}_a$	802.86	799.04
$\dot{m}_f$	2.4912	2.5180
A	2.19	4.3
W_{to}/S	316.73	324.59
T_f	288.15	300
T_{ic}	274.8	220
T_{inl}	486.15	374.98
$\dot{m}_{inl}$	0.138	0.127
$\dot{m}_{cb}$	0.134	0.158
Total exergy loss J	6.89×10^{11}	6.28×10^{11}

For the overall mission, an improvement of 8.85 % over the initial synthesis/design is made. Hence, the global optimization is obviously better than the local one of each subsystem, from where the original values come. Furthermore, the exergy based synthetic design shows the improvement in the exergy destruction for every mission phase and every subsystem.

An exergy analysis of the variables in different subsystem components for the optimal and original designs is presented in figure 3, (a) and (b) separately represent the flight phase of the cruise and descending. This exergy analysis shows which subsystem components and to what degree they contribute to the performance improvements that the energy synthesis design provides.



(a) Phase of cruise *(b)Phase of descending*

Fig. 3. Optimal and original designs of variables in different subsystems

5. Conclusions

An exergy analysis allows for quantitative assessment of thermodynamic irreversibility which occurs in different subsystems and components of aircraft. This technique creates a reliable basis for comparison between the losses of the different subsystems and components and shows where the most improvements could be made in order to develop the entire system by means of new technology or redesign. The exergy consumption of a more electric aircraft is evaluated in this paper. The propulsion subsystem contributes the majority of the irreversible loss of energy. In addition, the exergy based synthesis optimization shows possibility to reduce the energy consumption by changing the wing loading and fuel temperature as well as variables from other subsystems at the same time.

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