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Multi-objective optimisation of aircraft departure trajectories

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ABSTRACT

A multi-objective trajectory optimisation has been developed to minimise multiple environmental impacts (noise and exhaust emissions) from commercial airplanes. Three different non-gradient algorithms are used. First, a parameterization method is established for airplane departure trajectories, with path constraints considered where necessary. Second, a method to parameterize movement in the lateral plane based on a Bézier curve has been proposed to decrease the number of free parameters. The environmental impacts on target areas have been simulated by a comprehensive flight mechanics program. Finally, two posterior selection strategies based on preference function and monetisation approaches are used to evaluate the resulting Pareto solution set. A case study for a departure of an Airbus A320-211 with population distribution of residential communities around Manchester Airport (ICAO code: EGCC) is carried out with three different optimisers. We demonstrate that this simulation framework is able to solve trajectory optimisation problems with multiple simultaneous environmental objectives.

1. Introduction

Meeting community expectation in terms of sustainable development of commercial aviation remains a challenge, in spite of more stringent policies and regulations to control noise emission and exposure. The fact that the population within the 57 dBA contour for the four largest airports in the UK has fallen by about 30% during the 14 years ending in 2011 [1,2] appears not to diminish the perception that aircraft noise is worsening [3]. The problem is not only how to guarantee a quieter, cleaner and more efficient flight, but how to compensate the additional environmental cost to support the development of the entire aviation industry, whilst meeting public concerns.

Although the potential for eliminating the environmental pressure by novel engines and aircraft configuration design seems promising, solutions that can be applied to the existing fleet and technology should not be underestimated. New air traffic management concepts have emerged in the United States under the name of NextGen [4], in Europe under the name of SESAR [5] and in Japan under the name of CARATS (Collaborative Actions for Renovation Air Traffic Systems) [6], with the aim of satisfying increasingly diverse requirements for airlines and passengers and to relieve the environment pressure of aviation.

Previous studies have shown that aircraft noise and exhaust emissions can be significantly reduced by trajectory optimisation [7,8]. A trajectory optimisation tool named NOISHHH developed by Visser et al. [9,10] integrated a noise model, a geographic information system and a dynamics trajectory optimisation algorithm with the collocation method; this method converts the continuous optimal control problem into a finite-dimensional nonlinear programming problem [11]. Similar algorithms have been implemented in the optimisation methodology developed by Hartjes et al. [12] to solve multi-event aircraft trajectories problems. A multi-criteria optimisation strategy with the lexicographic-egalitarian technique is implemented by Prats et al. [13,14] to minimise the noise annoyance in Noise Sensitive Areas (NSA). Further studies showing a comparison between gradient-based methods was published by Khardi et al. [15], resulting in a preference towards the direct method.

Despite the effectiveness of the gradient- or derivative-based methods mentioned, difficulties arise when attempt is made to solve optimisation problems for discontinuous models. With the increasing complexity of current optimisation problems, there is no guarantee that optimisation problems can always be constructed with continuous models that can be differentiable. This shortcoming has led to the prosperity of several heuristic algorithms that are less computationally expensive, but do not need gradient information. This feature makes them more suitable and flexible for the optimisation problems described in this paper. A multi-objective mesh adaptive direct search method used by Torres et al. [16] aims to minimise noise and Nitrogen Oxides (NO_x) emissions for departing aircraft. Yu et al. [17,18] performed state parameterizations with Bernstein polynomials to discretise the noise impact optimi-

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Nomenclature

α	angle of attack, rad; image of preference value function	
β	coefficient of preference value function	
γ	flight path angle	rad
τ	free parameter, non-dimensional	
ϕ	bank angle	rad
χ	heading angle	rad
ω	inertia weight	
b	Bernstein basis polynomials	
c	PSO parameters	
f	fuel flow rate, kg/s; criterion	
g	gravitational acceleration	m/s^2
h	altitude	m
k	drag induced parameter	
m	aircraft mass	kg
n	load factor, preference value function	
p	preference value	
t	flight time	s
V	true airspeed, m/s; total preference value	
x	flight time, horizontal distance from aircraft to threshold of the runway	m
y	lateral distance from the aircraft to the centreline of the runway	m
C	aerodynamic force coefficient	
D	aerodynamic drag	
F_N	net thrust from all engines	N
Ma	Mach number	
N_1	engine rpm	%
P	percentage	
R	radius	m
S	wing area	m^2
B	Bézier curve function	
P	coordinate of control points	
$\boldsymbol{u}$	vector of control variables	
$\boldsymbol{x}$	vector of state variables	
AG	Multi-Objective Particle Optimisation based on Adaptive Grids	
DM	decision maker	
MOP	Multi-objective Optimisation Problem	
NSA	Noise Sensitive Area	
NSGA-II	Nondominated Sorting Genetic Algorithm II	
PSO	Particle Swarm Optimisation	
PE	Multi-objective Particle Optimisation based on Pareto Entropy	
RF	Radius-to-a-Fix	
SCC	Social Cost of Carbon	
UCNPP	Unit Cost of Noise Protection by a Population	

Subscripts

0	initial
f	final
c	control
L	lift
L_0	lift coefficient at zero angle of attack
L_α	slope of lift coefficient curve
D	drag
D_0	drag coefficient at zero lift
max	maximum
min	minimum

sation for arrival trajectories with a genetic algorithm. Similarly, Hartjes and Visser [19] applied genetic algorithms to departure flight path planning for noise abatement and emission reduction. Ho-Huu et al. [20] explored evolutionary algorithms based on decomposition (MOEA/D) for noise abatement trajectories.

Thus, there is evidence that non-gradient algorithms are suitable for solving this category of optimisation problems. However, due to the large number of free parameters, there is a less optimistic view, because of the unfeasibly large number of function evaluations required. Moreover, with adding further environmental parameters or different noise attributes, an optimal solution cannot be selected from the solution set, unless further algorithms are introduced.

In this study, a trajectory optimisation framework based on non-gradient algorithms is developed. A new parameterisation method is implemented to discretise the flight dynamics equation on both vertical and lateral planes with a limited number of free parameters. Two posterior selection strategies based on aggregated preference function and monetisation approach respectively are applied to select the optimal solution within the Pareto solution set. The details of the problem formulation are explained in section 2, including the description of the multi-objective trajectory optimisation problems for environmental impacts minimization. The next two sections describe the proposed parameterization method with its implementation and the posterior selection strategies for the optimised solutions. Section 5 presents a numerical example of which results demonstrate the optimised departure trajectory from Manchester Airport. The aircraft flight mechanics, aerodynamics, propulsion and acoustic models used in this work are built based on the configuration of Airbus A320-211 with CFM56 engines.

2. Problem formulation

2.1. Dynamics equations

A constrained trajectory optimisation problem is constructed with aircraft flight dynamics models, constraints of air traffic safety issues and cost functions of distinctive objectives. For the present scope, the aircraft is modelled as a rigid body with varying mass, aerodynamic, propulsive and gravitational forces. Some assumptions are made to simplify the problem: (1) flat and non-rotational Earth; (2) all forces acting on the aircraft through its centre of gravity; (3) zero angle between the engine thrust and the longitudinal axis of the aircraft; (4) small angle of attack α. Thus, a 3 degrees-of-freedom flight dynamics model with a set of differential algebraic equations associated with a variable mass can be simplified as:

$$\begin{cases} \dot{V} = \dfrac{F_N - mg\sin\gamma - D}{m} \\ \dot{\gamma} = \dfrac{L\cos\phi - mg\cos\gamma}{mV} \\ \dot{\chi} = \dfrac{L\sin\phi}{mV\cos\gamma} \\ \dot{x} = V\cos\gamma\sin\chi \\ \dot{y} = V\cos\gamma\cos\chi \\ \dot{h} = V\sin\gamma \\ \dot{m} = -f \end{cases} \tag{1}$$

where the state variables consist of true airspeed V, flight path angle γ, heading angle χ, bank angle ϕ, and three dimensional lo-