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Development of multiobjective trajectory-optimization method and its application to improve aircraft landing

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A B S T R A C T

The objective of this study is to develop a trajectory-optimization method using an efficient time-series flight simulation. Equations of motion (EoMs) were solved by estimating the time-series aerodynamics data construction. The aerodynamics of an arbitrary aircraft were estimated according to an aerodynamic database, which improved the efficiency via the Kriging method. To increase the accuracies of aerodynamic databases, additional data sets were acquired. The developed method was applied to the multi-objective problem of trajectory optimization for landing approaches. Two objective functions were considered: the minimization of the cost function, which indicates the optimal profile trajectory, and the minimization of the maximum acceleration. A Kriging model-based exploration with non-dominated sorting genetic algorithm-II was used as an optimizer. According to the results, as well as a comparison of the cases with and without the microburst effect, the microburst effect can potentially cause an overestimation of the aircraft trajectory by minimizing both the cost function and the maximum acceleration. The trajectory thus needs to be corrected to the nearest trajectory without a microburst effect, with optimal control angle and altitude. The trajectory optimization was affected by the initial sampling and additional samples of the aerodynamic database. This study shows the importance of this database for optimizing the trajectory analysis on the basis of the equation of motion.

1. Introduction

Several studies on the future of aircraft have been conducted [1–4]. The blended wing body (BWB) type aircraft [1–3] has been widely studied as a possible concept to reduce the noise and the drag drastically. The “double-bubble fuselage” concept [4] has also been proposed. To develop a novel shape of future aircraft, trajectory optimization technology is desirable to determine the dynamic characteristics. In particular, aircraft designs face hazardous situations during takeoff and landing [5]. A typical unexpected weather condition is a called a microburst and is classified as a dangerous situation for 4% [6] of aircraft takeoffs and landings [5,6]. Therefore, engineers must investigate this effect to ensure the safety of airplanes [7–11].

Many studies have investigated aircraft motion in several hazardous weather conditions. Flight simulation by solving equations of motion (EoMs) considering nonlinearity was applied to solve the problem of hazardous situations during takeoff and landing [10,11]. In [11], the trajectory to encounter the microburst was shown by solving quadratic programming. Many cases were compared [7,10,11]; however, global aerodynamic and design knowledge was not covered. As a result, many of the trajectory optimization studies focused on control strategies to overcome hazardous situations and did not consider the effect of aerodynamic data in detail. Genetic algorithms (GAs) were applied to optimize the economic and environmental efficiency of air traffic by civilian aircraft that travel from city to city [12]. Remarkably, a global optimum for the multiobjective problem could be determined; however, the knowledge discovery from a set of solutions was not the focus.

Increasing demand of civilian aircraft means that the frequencies of take-off and landing at airports should increase [13–15]. Therefore, better safety and higher economic and environmental performance will be required. Thus, we focused on the application of the global optimization technique and the knowledge discovery for the aircraft trajectory surrounding airports, with consideration of hazardous situations.

In this study, the Kriging method based on global optimization [16–18] was employed to determine the set of global optimum solutions. We attempt to use the aerodynamic derivatives estimated by the United States Air Force (USAF) stability and control DATCOM [19] as exact solution. To improve the accuracies of the aerodynamic database, additional data sets were acquired by using a ge-

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Nomenclature

J	cost function	
acc	acceleration	m/s^2
$x(t)$	state position with respect to the horizontal axis	
$u(t)$	control angle position	
$W(t)$	wind component	
z, x	altitude and horizontal distances	
α	angle of attack	deg
Ma	Mach number	
θ	pitch angle	deg
δe	elevator deflection angle	deg
$\boldsymbol{\chi}$	vector of design variable	
$f(\boldsymbol{\chi})$	stochastic process	
μ	global model	
$\varepsilon(\boldsymbol{\chi})$	local deviation from μ at $\boldsymbol{\chi}$	
σ^2	process variance	
$k(\boldsymbol{\chi}, \boldsymbol{\chi}')$	correlation functions	
i	sampling	
φ	value of parameter	
h	distance between the two locations $\boldsymbol{\chi}$ and $\boldsymbol{\chi}'$	
n	sample numbers	
$\boldsymbol{\Theta}$	hyper-parameters	
$\boldsymbol{R}$	matrix whose (i, j) entry is $k(\boldsymbol{\chi}^{(i)}, \boldsymbol{\chi}^{(j)})$	
$\mathbf{1}$	unit vector	
EI	expected improvement	
q	pitch rate $(= d\theta/dt)$	rad/s
C_X	axial force coefficient	
C_M	pitching momentum coefficient	
C_L	lift coefficient	
C_D	drag coefficient	
C_Z	vertical force coefficient	
ρ	density	kg/m^3
V	velocity	m/s
S	reference wing area	m^2
m	mass	kg
I_{yy}	moment inertia	kg/m^4
g	gravity acceleration	m/s^2
W	wind speed by microburst	m/s
KW	the maximum value of the horizontal wind	m
$X1$	source position of a microburst	
XL	length of a microburst	

Subscript

max	maximum value	
min	minimum value	
ref	reference value	
f	final condition	
0	initial condition	
z	vertical axis component	
x	horizontal axis component	
α	differential of angle of attack	deg
q	differential of pitch rate	deg
δe	differential of elevator angle deflection	deg

Superscript

..	second order term

netic algorithm. The developed optimization method was applied for trajectory optimization with two objectives. The first objective was to minimize the cost function of the final glide flight path during landing, and the second was to minimize the maximum acceleration. These objectives should be considered for arbitrary aircraft to ensure that passengers are comfortable after experiencing hazardous situations.

This paper is organized as follows: First, a trajectory optimization problem is addressed in Section 2. Subsequently, the method of multiobjective trajectory-optimization is introduced based on the Kriging-based design exploration, called efficient global optimization (EGO), in Section 3. In Section 4, the results are presented and discussed. This section contains the cross-validation results of the aerodynamic model, comparison results of the non-optimized and non-dominated solutions for the with/without microburst situation via the time-series trajectory. In addition, the control optimization is discussed.

2. Definition of a trajectory optimization problem

Optimal trajectories are acquired by solving the multiobjective design problem, which has two objective functions: One is the minimization of cost function J [10,11] and the other is the minimization of maximum acceleration $acc_{\max}$ [20,21] during landing, as shown in Fig. 1. Therefore, an overestimation of the flight path can be avoided and the additional load to the aircraft, i.e., passengers and payloads, in the range of effective microbursts can be reduced [20,21].

$$\begin{cases} \text{Minimize}: J \\ \text{Minimize}: acc_{\max} \end{cases} \tag{1}$$

Here, J is an optimal trajectory altitude in the flight path for the related solution vector, based on the flight condition [10,11]. J can be expressed as

$$J = \phi\big[x(t_\mathrm{f})\big] + \int_{t_0}^{t_\mathrm{f}} L\big[x(t), u(t), W(t), t\big]dt \tag{2}$$

where $\phi[x(t_\mathrm{f})]$ is the flight-path angle in the final landing trajectory and $\int_{t_0}^{t_\mathrm{f}} L[x(t), u(t), w(t), t]dt$ is the cost-function integration, which includes a vector comprising the state condition $x(t)$, control condition $u(t)$, and microburst term $W(t)$. Then, $L[x(t), u(t), W(t), t]$ can be expressed as

$$L\big[x(t), u(t), W(t), t\big] = \big\{2\big[\big(z - z(0)\cos\alpha_0 - \big(x - x(0)\sin\alpha_0\big)\big)\big]^2 + 0.04\big[\delta e - \delta e(0)\big]^2\big\} \tag{3}$$

J indicates the optimal landing trajectory profiles of the aircraft with and without consideration of the microburst effect, where the distances are expressed in meters.

Acceleration of the aircraft has to be reduced to avoid stalling of and the damage to the aircraft [20,21]. The $acc_{\max}$ is the resultant acceleration during landing, expressed as,

$$acc_{\max} = \sqrt{acc_x^2 + acc_z^2} \tag{4}$$

The design variables for the optimization problem expressed by Eq. (1) are the initial values of $\alpha(0)$, $Ma(0)$, $\theta(0)$, and $\delta e(0)$.$\alpha(t)$, $Ma(t)$, $\theta(t)$, and $\delta e(t)$ were at regular intervals and interacted during the solving of the equations of motion.

3. Method of multiobjective trajectory optimization

Three phases were undertaken for the proposed trajectory optimization, as shown in Fig. 2. First, the aerodynamic database to be predicted by the Kriging-based database improvement [17,22,23] was constructed (① in Fig. 2). Then, the trajectory evaluation and its optimizations were performed by solving the 3DoF EoM