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A parametric study of fixed-wing aircraft perching maneuvers

D.M.K.K. Venkateswara Rao [a,*], Hui Tang [b], Tiauw Hiong Go [c]

[a] School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore
[b] Department of Mechanical Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong SAR, China
[c] Mechanical and Aerospace Engineering Department, Florida Institute of Technology, Melbourne, FL 32901, United States

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ABSTRACT

This paper presents a trajectory optimization-based study for identifying the influences of different fixed-wing aircraft parameters on perching maneuvers. Perching trajectories, which involve climbing for landing with a near-zero speed, are optimized to minimize the unwanted altitude gain, herewith referred to as undershoot. Undershoot has a complex relationship not only with the control inputs, but also with the aircraft geometry and features, such as stability characteristics, controllability, and thrust available. To facilitate this parametric study, an aerodynamic modeling tool is developed, which combines a nonlinear vortex correction method with the Leishman's state-space form of Wagner's unsteady model. This tool is used for in-flight aerodynamics evaluation during the optimization of the perching maneuvers. The perching solutions – minimum undershoot and trajectory length – are then computed, and the effects of key parameters of the maneuver are studied. It is found that a high aspect ratio, high thrust available, optimal placement of the center of gravity, relaxed terminal velocity constraints, low zero-lift drag, and headwind reduce the spatial requirements for the maneuver. Furthermore, it is confirmed that a high angle-of-attack maneuver is not critical for very low speed perching.

1. Introduction

Fixed-wing aircraft perching can be described as a swift, aggressive, high angle-of-attack (AOA) and unconventional landing maneuver. During this maneuver, the aircraft starts with a relatively high speed, uses a combination of aerodynamic, thrust and gravity forces to pull up rapidly, so that it converts its kinetic energy to potential energy through a climb and lands with a near-zero speed. To perform this maneuver, the aircraft may need to dive first to reach the required initial high-speed state for sustained climbing. These two phases of the maneuver are defined as dive and climb phases, and the altitude gain during the climb phase is defined as undershoot.

Due to the climb phase, the perching aircraft requires an elevated landing location, which poses a new spatial constraint for the maneuver. For this reason, perching trajectories are often optimized to minimize the undershoot [25]. Through optimization, control inputs can be determined to accomplish perching with minimum undershoot. However, undershoot depends not only on the control inputs, but also on the aircraft features, such as the wing shape and dimensions, stability characteristics, controllability, and thrust available. Thus, it is important to know how changes of these features influence the perching maneuver, so that the design of the aircraft can be optimized to carry out the perching with reduced undershoot and spatial requirements. With this motivation, a parametric study on perching maneuvers of a fixed-wing aircraft is conducted in this paper.

Current literature on understanding the effects of different parameters on perching maneuver is very limited. Wickenheiser and Garcia carried out a very basic and preliminary study on the effects of two aircraft parameters – maximum thrust available and static margin [25]. It is shown that high thrust available and positive static margin can minimize the undershoot, and unconventional morphing features such as the variable-incidence wing and rotating tail can reduce the spatial bounds of the maneuver. Rao and Go studied and compared the effects of coupled and decoupled aerodynamic and thrust vectoring features on perching maneuver [21]. It is shown that thrust vectoring is more effective in minimizing the undershoot as compared with aerodynamic vectoring [15–17].

The strategy adopted for the present parametric study is explained as follows. An aircraft model, based on a commercially available radio-controlled airplane, is chosen as the reference model. Optimal perching solutions – the minimum undershoot and trajectory length – are computed for this model and are

* Corresponding author.
E-mail addresses: dmohankkvr@gmail.com (D.M.K.K. Venkateswara Rao), htang@polyu.edu.hk (H. Tang), tgo@fit.edu (T.H. Go).

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Table 1
Reference aircraft's mass and geometry properties.

Quantity	Value
mass m	0.8 kg
chord c	0.25 m
span b	1 m
wing surface area S_{wing}	0.25 m^2
tail surface area S_{tail}	0.04 m^2
moment of inertia I_{yy}	0.1 $kg\,m^2$
CG position x_{cg}	0.0 m
wing quarter-chord position $x_{c/4_{wing}}$	−0.0625 m
tail quarter-chord position $x_{c/4_{tail}}$	−0.71 m
gravity g	9.8 m/s^2
air density ρ	1.225 kg/m^3

treated as the reference solutions. Parameters of interest, i.e., target terminal-velocity, maximum thrust-to-weight ratio, maximum AOA, aspect ratio, static margin, wing-sweep angle, and zero-lift drag coefficient, are assumed to have a significant influence on the perching maneuver, and are selected for the study. Optimal perching solutions are computed by varying each of these parameters separately in a valid range. To facilitate the comparison, the computed optimal values are normalized using the corresponding optimal values of the reference aircraft model. From the variation of optimal undershoot and trajectory length values, the influence of each parameter on the perching maneuver can be identified. Since the change of some of the parameters modifies the aircraft's geometry, frequent evaluation of the aircraft's aerodynamics is expected. For this, an aerodynamic modeling tool based on the Nonlinear Vortex Correction Method (NVCM) [11], which ensures accuracy, especially in the post-stall regime, is developed. The original NVCM only estimates the steady-state values of lift, drag and moment for a given aircraft geometry and state. To account for the unsteady aerodynamics, Leishman's state-space model [14] of Wagner's function [9,10] is used. With this framework, the parametric study of fixed-wing aircraft perching maneuver is carried out.

Compared with the indoor perching experiments on micro aerial vehicles by Cory and Tedrake [6] and Paranjape et al. [19], where only aerodynamic drag is used for deceleration, the perching strategy adopted in this paper uses both aerodynamic drag and gravity for deceleration, which makes it more applicable for larger aircraft. This strategy is similar to the approach used by Wickenheiser and Garcia [24] for the Martian lander.

The rest of the paper is organized as follows. In Section 2, details of the aircraft model, the NVCM aerodynamic model, and the optimization formulation of perching trajectories are presented. Results of the parametric study are presented and discussed in Section 3. Finally, the conclusions are presented in Section 4.

2. Framework

In this section, a computational framework is developed for the parametric study. Details of the reference aircraft model, development of the NVCM based aerodynamic model, and computation of the optimal perching solutions are described.

2.1. Reference aircraft model

The reference aircraft model considered in this study is chosen from Ref. [18], in which the focus is on the optimization of transition maneuvers between hover and cruise. It has a conventional fixed-wing configuration, and its mass, inertia, and other geometric properties are listed in Table 1.

2.2. Aerodynamic model

During the parametric study, changes in some of the parameters cause modifications to the aircraft geometry and thereby its aerodynamics. To evaluate the changing aerodynamics, an NVCM-based aerodynamic model [11] is used.

2.2.1. Nonlinear vortex correction method

Similar to the Vortex Lattice Method (VLM) [2], NVCM discretizes the lifting surfaces, i.e., wing and tail, into multiple small quadrilateral sections called panels. To each of these panels, a horseshoe vortex of unknown strength is attached at the panel's quarter-chord line. In VLM, the strengths of the bound vortices are determined by satisfying the no-flow-through boundary condition at the control points located at the center of the panel's three-fourth chord line. In NVCM, these strengths are determined in such a way that the lift calculated from the circulation matches the corresponding airfoil data. An aerodynamic lookup table for a given airfoil, including the post-stall regime, can be obtained from literature or wind-tunnel experiments. Since the present study involves post-stall aerodynamics, the use of NVCM for the aerodynamic modeling is clearly advantageous.

To model the aerodynamics of the perching aircraft using NVCM, a vortex grid superimposed with the free stream is considered. The local velocity, $\vec{V}_m$, at the center of the quarter chord line of a panel m is a summation of the velocity induced by the bound vortices, $\vec{V}_i$, and the free stream velocity, $\vec{V}_\infty$

$$\vec{V}_m = \vec{V}_\infty + \vec{V}_i \tag{1}$$

Expressing $\vec{V}_m$ in terms of its component velocities as

$$\vec{V}_m = u_m\hat{\mathbf{i}} + v_m\hat{\mathbf{j}} + w_m\hat{\mathbf{k}} \tag{2}$$

the local AOA can be obtained by

$$\alpha_m = \tan^{-1}\left(\frac{w_m}{u_m}\right) \tag{3}$$

Using the airfoil data, the aerodynamic forces on the panel m can be calculated by

$$dL_{m_{Lookup}} = \frac{1}{2}C_L(\alpha_m)\rho V_m^2 dA_m \tag{4}$$

$$dD_{m_{Lookup}} = \frac{1}{2}C_D(\alpha_m)\rho V_m^2 dA_m \tag{5}$$

where ρ is the density, V_m is the magnitude of $\vec{V}_m$, and dA_m is the surface area of the panel. $C_L(\alpha_m)$ and $C_D(\alpha_m)$ are the lift and drag coefficients from the lookup table, respectively. On the other hand, the lift on the panel can also be calculated from the Kutta–Joukowski theorem

$$dL_m = \rho V_m \Gamma_m dS_m \tag{6}$$

where dS_m is the length of the vortex bounded to the panel. According to NVCM, the lifts obtained from the aerodynamic table and the Kutta–Joukowski theorem should match with each other

$$dL_m = dL_{m_{Lookup}} \tag{7}$$

When this matching condition is applied to all the N panels, the following system of nonlinear algebraic equations is obtained

$$f(\Gamma_1, \Gamma_2, \cdots, \Gamma_N) = \begin{bmatrix} f_1(\Gamma_1, \Gamma_2, \cdots, \Gamma_N) \\ f_2(\Gamma_1, \Gamma_2, \cdots, \Gamma_N) \\ \vdots \\ f_N(\Gamma_1, \Gamma_2, \cdots, \Gamma_N) \end{bmatrix} = \begin{bmatrix} dL_1 - dL_{1_{Lookup}} \\ dL_2 - dL_{2_{Lookup}} \\ \vdots \\ dL_N - dL_{N_{Lookup}} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{8}$$