Aerospace Science and Technology 55 (2016) 400–408

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Numerical simulation of pararotor dynamics: Effect of mass displacement from blade plane

Joaquín Piechocki [a,*,1], Vicente Nadal Mora [a,1], Ángel Sanz-Andrés [b,2]

[a] Universidad Nacional de La Plata, (1900) La Plata, Buenos Aires, Argentina
[b] Universidad Politécnica de Madrid, E-28040, Madrid, Spain

ARTICLE INFO

Article history:
Received 1 November 2013
Received in revised form 24 November 2015
Accepted 3 April 2016
Available online 21 April 2016

Keywords:
Decelerator
Numerical simulation
Rotary wing

ABSTRACT

The pararotor is a biology-inspired decelerator device based on the autorotation of a rotary wing, whose main purpose is to guide a load descent into a certain planetary atmosphere. This paper focuses on a practical approach to the general dynamic stability of a pararotor whose center of mass is displaced from the blade plane. The numerical simulation tool developed is based upon the motion equations of pararotor flight, utilizing a number of simplifying hypotheses that allow the most influencing factors on flight behavior to be determined. Several simulated cases are analyzed to study the effect of different parameters associated with the pararotor configuration on flight dynamics, particularly the center of mass displacement from the blade plane. It was confirmed that the ability to reach stability conditions depends mainly on a limited number of parameters associated with the pararotor configuration: the relationship between principal moments of inertia, the planform shape (associated with blade aerodynamic coefficients and blade area) and the vertical distance between the center of mass and the blade plane. As a result different types of equilibrium solutions are found and the effect of each parameter is characterized. A bifurcation in the stability shape to a precessing conical rotation, not previously found in the linear stability analysis, is predicted by this numerical model.

1. Introduction

The pararotor is a biomimetic rotary wings decelerator, unpowered, and potentially deployable whose main practical use is to aerodynamically decelerate a load descending into a certain planetary atmosphere or to perform measurements during descent. Such a probe offers several advantages over other recovery techniques: simplicity, controlled deceleration, maneuvering capabilities and potential land recovery. Also, this decelerator type is of interest, for instance, for the measurement of atmospheric conditions around airports for aviation operations support, or the exploration of planetary atmospheres.

Works concerning the deceleration and control of falling bodies were published by Shpund and Levin [1–4], in the area of rotating parachutes. Karlsen, Borgström and Paulsson [5] worked on winged bodies for submunition applications. They reported on the advantages of the pararotor over the parachute: lower sensitivity to lateral winds, parachute deployment problems, lower precession movements, and higher falling velocity.

The flight of samara wings has similarities with pararotors. Seter and Rosen [6,7] studied numerically the influence of different parameters on samara flight stability. Crimi [8] has studied a rotating body with only one wing for submunition applications. He searched for a body that performed periodic movements.

Previous work has been carried out concerning modeling the stability of a pararotor, mainly by Nadal Mora, Sanz-Andres and Piechocki [9–17]. They conducted investigations concerning the stability behavior of pararotors whose blades where aligned with the center of mass of the whole device. They developed an analytical model that predicts the dynamic behavior under different device configurations.

An analytical linearized model was described by Piechocki et al. [17] presenting four different cases of analyses that are revisited in the current work.

Seter and Rosen [18] presented the modeling of multibody systems for a helicopter.

Pararotor decelerator potential has been investigated by different authors [19–22], who consider applications that are centered

* Corresponding author.
E-mail address: joaquin.piechocki@ing.unlp.edu.ar (J. Piechocki).

[1] Assistant Professor, Grupo de Ingeniería Aplicada a la Industria, Departamento de Aeronáutica, Facultad de Ingeniería, Calle 116 entre 47 y 48.

[2] Full Professor, Instituto Universitario de Microgravedad "Ignacio Da Riva," Escuela Técnica Superior de Ingenieros Aeronáuticos, Plaza Cardenal Cisneros, 3.

http://dx.doi.org/10.1016/j.ast.2016.04.004
1270-9638/

Nomenclature

C_D	drag coefficient of the blade
$C_{L\alpha}$	slope of the curve lift vs. angle of attack of the blade
C_{DM}	model drag coefficient
C_M	center of mass
C_P	center of pressure
$\mathbf{F}_{gc}$	weight force vector ... N
$\mathbf{h}$	kinetic momentum ... $\mathrm{kg\,m/s^2}$
I_i	principal moments of inertia, $i = 1, 2, 3$ ... $\mathrm{kg\,m^2}$
k	vertical velocity to blade-tip-speed ratio
k_{ij}	ratio of coordinates of the center of pressure of the blade j in axis i direction, r_{ij}/r_{11}
k_e	dimensionless parameter used for the stability analysis
$\mathbf{n}_i$	direction perpendicular to blade i surface, $i = 1, 2$
S	area of one blade ... $\mathrm{m^2}$
$\mathbf{T}_\mathrm{M}$	transformation matrix to convert vectors from the body fixed frame to the inertial frame
$\mathbf{V}_{ri}$	relative velocity to the i blade ... m/s
V_t	pararotor descent velocity ... m/s
v_h	axial hovering velocity ... m/s
v_i	induced velocity ... m/s
α	angle of attack ... rad
$\beta_0, \beta_1, \beta_2$	mean pitch angle, pitch angle of blade 1, 2, respectively ... rad
θ	nutation angle ... rad
φ	spin angle ... rad
ψ	precession angle ... rad
$\boldsymbol{\omega}$	angular velocity ... rad/s
ω_{12}	angular velocity projected in the 1–2 plane, or transversal angular velocity ... rad/s

in mission concepts requiring controlled descent, low-velocity landing, and atmospheric research capability on planet exploration.

The main objective of the current work is to develop and validate a numerical simulation tool to describe pararotor flight modes to determine the stability behavior of a pararotor considering different configuration parameters, particularly the effect of the distance between the blade plane and the center of mass (illustrated in Fig. 1) and to study dynamic effects of parameters associated with the device configuration.

It is worth mentioning that the present paper extends the studies previously developed [17] considering nonlinear effects in the pararotors dynamics and their results on pararotor flight behavior. Those nonlinear terms are the result of using Newton–Euler equations for a rigid body excited with aerodynamic loads coupled with inertial phenomena. In the analytical model [17] second order terms were consistently neglected by considering that the following parameters are of small magnitude: blade pitch angle, relationship between descent rate to the velocity induced in the blades by rotation, distance of blade center of pressure in $\mathbf{e}_2$ direction from center of mass, blade drag aerodynamic coefficient. The nature of Newton–Euler equations of a rigid body under the effect of aerodynamic forces (that are blade relative velocity dependent) is in general nonlinear. The validity of the linear analytical model [17] is restricted to the vicinity of an equilibrium point. This numerical approach is a useful potential tool that allows the stability limits, the effects of configurational parameters, and the flight mode of future practical devices to be more accurately defined. This modelization includes neither simplificative assumptions (magnitude orders neglecting criteria) nor linearization of the system near the equilibrium solutions, as developed in [17]. The significance of this work is that the nonlinear factors effects on flight dynamics can be considered practically, not only in terms of response time, but also in stability limits and flight mode, particularly with pararotors flying near their stability limits defined in [17].

The current research shows solutions that cannot be reached by previous modelization, and so, a deeper understanding of the phenomena can be reached, with its positive practical impact on pararotor design.

2. Mathematical and numerical models

The approach chosen in this work to study the pararotor dynamic behavior was to build an analytical model of a pararotor based on the development of the complete motion equations, including aerodynamic forces and torques generated by the blades and to compute numerically the evolution of the system from a particular initial flight attitude, different from the final equilibrium state. So, the analyses performed responds to the observation of patterns over specific cases. The effect of k_{31}, the dimensionless distance of the center of mass to the blade plane in the falling direction, is analyzed together with a number of geometrical and aerodynamical parameters.

Induced velocity, v_i, was not directly included in the model, following similar assumptions of former studies [16]. Other studies [21] indicated that real low aspect ratio rotary wing shows an induced power correction factor (that can be defined as the factor that modifies rotor classic momentum theory when considering nonideal blade physical effects), κ, of about 2 or greater. This fact indicates that the relationship of descent rate and axial hovering velocity, v_h, is greater than 2, thus in a windmill brake state axial descent [22]. The current model focuses on the assumption of small induced velocity, in the windmill brake state. Large induced power correction factors associated with low aspect ratio wing are consistent with this hypothesis. Vertical tunnel tests performed [20] using different small aspect ratio wings pararotors showed induced velocities of 15% of the descent velocity on average, evidencing that the simplificative hypothesis is associated with a representative flight range.

Flow model for axial descent in windmill brake state [22] indicates that the sensibility of induced velocity, v_i, to descent rate, decreases with the descent velocity to the hovering velocity ratio, V_t/v_h. This means that vertical velocity disturbances influence on induced velocity depends on the v_i/v_h magnitude, and so on κ.

However, the effect of induced velocity is included in the values of lift, lift slope and drag coefficients, C_L, $C_{L\alpha}$ and C_D, which are determined from experiments [16]. This experimental work was performed in operational conditions of a pararotor model, so the effect of v_i will result in an increment of the magnitudes of lift and drag if free stream velocity over the blades is considered. As a consequence, the model will be developed associated with this experimental data, that will define an operating range of validity, over which the lift slope can be approximated as linear. This range is defined in the incompressible regime.

The system analyzed is a pararotor flying in an autorotation regime, modeled as an inertial cylindrical body with two identical low-aspect-ratio flat blades which rotates at angular velocity $\boldsymbol{\omega}$ and falls vertically at speed V_t. The geometry is defined in Figs. 1 and 2. The body-fixed reference frame, 1, 2, 3, has its origin at the center of mass and directions $\mathbf{e}_1$, $\mathbf{e}_2$, $\mathbf{e}_3$. The axes 1, 2, 3 are the principal axes of the body. The inertial reference frame is X, Y, Z; its axes have the directions $\mathbf{i}, \mathbf{j}, \mathbf{k}$. The blades are located on a plane parallel to the plane 1, 2, in the direction $\mathrm{P_1P_2}$.