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A passive method to stabilize an airborne vehicle

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Abstract

A method of augmenting an airborne vehicle for short-period dynamics and stability by passive means is presented in this study. A trajectory-phase disturbance rejection capability is achieved for an unguided fin-stabilized vehicle by flexible mounting of the fins to the vehicle body. The deflecting fins lag the body oscillation such that the harmonic oscillation can be quickly dampened. The amount of fin deflection may be chosen by a hinge-line location; among other things, the vehicle damping behaviour is largely determined by this choice. Linear theory is applied and 6-DOF simulations are carried out to demonstrate the approach suitability for the task.

Keywords: Dispersion reduction; Passive control; Smart structure

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1. Introduction

An unguided vehicle's atmospheric flight is sensitive to external disturbances particularly at the initial stage of a trajectory. The deviations at the early phase may become large at the end of a flight path. Furthermore, the guided vehicles may fly part of a trajectory without an active flight controlling device, and therefore some additional damping may be required. Random disturbances cause vehicle oscillation about the centre of ~~the~~ mass, and this should be damped out as soon as possible. One way to relieve disturbance effects is to use a smart structure approach. A good example is a gimballed nose which reduces the nose lift. This subject has been studied extensively by Goddard [1], Kranz [2], Schmidt and Donovan [3], Barrett and Stutts [4], and Costello and Agarwalla [5]. Costello and Agarwalla [5] used 6-DOF computations to show that the impact point accuracy can be significantly improved by means of a moveable nose.

Another approach for passive flight control is to use an internal moveable mass in the vehicle, e.g. in the studies published at least by Hodapp [6], and Frost and Costello [7]. A further approach is to allow lengthening of the vehicle body in flight thus obviously benefiting the vehicle's damping properties, which has also been one of the topics of this branch of science.

The capability of flexibly mounted fins to dampen such disturbances is studied in this paper. The effect of deformable fins on a vehicle's passive control is documented by Underhill [8]. However, in this paper the fins are assumed to be rigid and also very light compared to the entire vehicle mass and no aeroelastic phenomena are considered. Additionally, the vehicle is assumed to be sufficiently rigid that the fin movement initiates no unwanted resonance phenomena.

Deflecting fins may be attached to the nose-part of a vehicle to provide obviously the same flight behaviour; however, the tail-mounted fins are given closer attention in this study. A

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Nomenclature

A	axial force
C_A	axial force coefficient, A/qS
C_D	drag coefficient, D/qS
C_L	lift coefficient, L/qS
C_m	pitch moment coefficient, M/qSd
$C_{m\alpha}$	pitch moment coefficient slope, $\partial C_N/\partial\alpha$
$C_{m\delta}$	control derivative, $\partial C_m/\partial\delta$
C_{mq}	pitch damping moment coefficient, $\partial C_m/\partial\widehat{q}$
$C_{Z\alpha}$	normal force coefficient slope, $\partial C_Z/\partial\alpha$
$C_{Z\delta}$	control derivative, $\partial C_Z/\partial\delta$
D	drag force
d	diameter
I_y	lateral moment of inertia
K_p, K_{pMag}	proportional gains
L	lift force
L	rolling moment
l	length
M	pitch moment
m	mass
N	yawing moment
q	kinetic pressure, $½\rho V^2$
q, r	angular velocity
$\widehat{q}$	dimensionless angular velocity, $qd/2V$
S	reference area, $\pi d^2/4$
s	*LaPlace*-variable
V	velocity
Z	normal force
α	angle of attack
δ	fin deflection angle
δ_c	commanded fin deflection angle
ρ	air density
ζ_f	fin turning damping ratio
ω_f	fin turning natural frequency

flexible hinge-line location is varied and the effects on a vehicle's dynamics are investigated by means of linear theory and 6-DOF simulations. In practice, variation in the longitudinal position of the hinge-line in computational studies is carried out by chancing a gain value. The values applied for the fin movement damping ratio in the simulations are assumed to be achieved mechanically and/or with the aid of aerodynamic fin damping. Obviously the flexible fin attachment may require a fin-locking mechanism under some circumstances before the free-flight phase of a vehicle.

2. Computational model and vehicle schematics

The dynamics of an airborne fin-stabilized vehicle is first studied using the linear theory. The results obtained are then verified by 6-DOF simulations. The 6-DOF equations are written in a non-spinning frame and a typical setup is employed as documented in Ref. [9].

Fig. 1. Airborne vehicle oscillatory behaviour after a disturbance.

An example of a vehicle oscillation after a disturbance (a launch for example) is given in Fig. 1.

The short-period dynamics of a vehicle is augmented and the approach in this study is to delay the fins' deflection. The turning lag of the fins is modelled by applying a second-order transfer function, and a damping ratio ζ_f and a natural frequency ω_f are chosen in such a way that the proper lag is obtained for a disturbance rejection. The stabilizing fins are assumed to deflect with a body angle of attack due to the air pressure. A "commanded" deflection (corresponding to a steady-state value) is obtained from a relation:

$$\delta_c = K_p\alpha \tag{1}$$

where α in Eq. (1) denotes a vehicle's total angle of attack, which is the angle between a velocity vector and a body centreline. Fig. 2 illustrates a body-fixed frame and the angle of attack defined. The gain K_p value is determined by the hinge-line location, fin details, and flexible joint properties, etc.

The fin numbering system and positive turning directions applied in the study are depicted in Fig. 3 as viewed from the rear of a vehicle. A fin positive deflection causes an anticlockwise rolling moment, which is another definition used in the literature but no consensus exists concerning the issue (Zipfel [10]).

An equivalent fin concept is applied and, for example, a corresponding pitch deflection for the geometry in Fig. 3 is obtained from the following formula

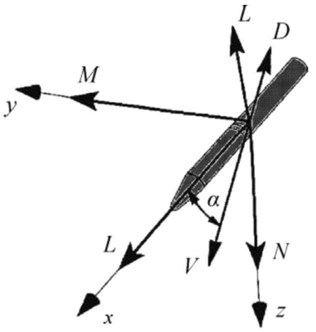

Fig. 2. The vehicle body-fixed coordinate system. Positive moment directions are also depicted. The total angle of attack α is the angle between the x_b-axis and the velocity vector *V*. The applied aerodynamic forces present are those in a wind coordinate system (D = Drag and L = Lift).