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Effect of multiple engine placement on aeroelastic trim and stability of flying wing aircraft

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ABSTRACT

Effects of multiple engine placement on flutter characteristics of a backswept flying wing resembling the HORTEN IV are investigated using the code NATASHA (Nonlinear Aeroelastic Trim And Stability of HALE Aircraft). Four identical engines with defined mass, inertia, and angular momentum are placed in different locations along the span with different offsets from the elastic axis while fixing the location of the aircraft c.g. The aircraft experiences body freedom flutter along with non-oscillatory instabilities that originate from flight dynamics. Multiple engine placement increases flutter speed particularly when the engines are placed in the outboard portion of the wing (60–70% span), forward of the elastic axis, while the lift to drag ratio is affected negligibly. The behavior of the sub- and supercritical eigenvalues is studied for two cases of engine placement. NATASHA captures a hump body-freedom flutter with low frequency for the clean wing case, which disappears as the engines are placed on the wings. In neither case is there any apparent coalescence between the unstable modes. NATASHA captures other non-oscillatory unstable roots with very small amplitude, apparently originating with flight dynamics. For the clean-wing case, in the absence of aerodynamic and gravitational forces, the regions of minimum kinetic energy density for the first and third bending modes are located around 60% span. For the second mode, this kinetic energy density has local minima around the 20% and 80% span. The regions of minimum kinetic energy of these modes are in agreement with calculations that show a noticeable increase in flutter speed if engines are placed forward of the elastic axis at these regions.

1. Introduction

Flying wing aircraft are typically flexible lightweight aircraft with high aerodynamic performance. They may exhibit body-freedom flutter when the short-period mode of the aircraft couples with the first symmetric elastic bending and torsion mode; see Chipman et al. (1984), Gyorgy-Falvy (1960), Love et al. (2005), and Myhra (1998). Due to the absence of a vertical tail, a static flight dynamic instability, which involves the yawing rotation of the aircraft in the horizontal plane, is usually captured in stability analyses and suppressed by control systems of the aircraft; see Chipman et al. (1984), Love et al. (2005), Moore (2010), Stenfelt and Ringertz (2009), and Myhra (1998).

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Nomenclature

a	deformed beam aerodynamic frame of reference
b	undeformed beam cross-sectional frame of reference
B	deformed beam cross-sectional frame of reference
$\mathbf{b}_i$	unit vectors in undeformed beam cross-sectional frame of reference (i=1, 2, 3)
$\mathbf{B}_i$	unit vectors of deformed beam cross-sectional frame of reference (i=1, 2, 3)
c	chord
$c_{m\beta}$	pitch moment coefficient with respect to flap deflection (β)
$c_{l\alpha}$	lift coefficient with respect to angle of attack (α)
$c_{l\beta}$	lift coefficient with respect to flap deflection (β)
e_1	column matrix $\lfloor 1\ 0\ 0 \rfloor^T$
e	offset of aerodynamic center from the origin of frame of reference along $\mathbf{b}_2$
f	column matrix of distributed applied force measures in $\mathbf{B}_i$ basis
F	column matrix of internal force measures in $\mathbf{B}_i$ basis
$\mathbf{g}$	gravitational vector in $\mathbf{B}_i$ basis
H	column matrix of cross-sectional angular momentum measures in $\mathbf{B}_i$ basis
i	inertial frame of reference
$\mathbf{i}_i$	unit vectors for inertial frame of reference (i=1, 2, 3)
I	cross-sectional inertia matrix
k	column matrix of undeformed beam initial curvature and twist measures in $\mathbf{b}_i$ basis
K	column matrix of deformed beam curvature and twist measures in $\mathbf{B}_i$ basis
m	column matrix of distributed applied moment measures in $\mathbf{B}_i$ basis
M	column matrix of internal moment measures in $\mathbf{B}_i$ basis
P	column matrix of cross-sectional linear momentum measures in $\mathbf{B}_i$ basis
r	column matrix of position vector measures in $\mathbf{b}_i$ basis
u	column matrix of displacement vector measures in $\mathbf{b}_i$ basis
V	column matrix of velocity measures in $\mathbf{B}_i$ basis
x_1	axial coordinate of beam
β	trailing edge flap angle
γ	column matrix of 1-D generalized force strain measures
Δ	identity matrix
κ	column matrix of elastic twist and curvature measures (1-D generalized moment strain measures)
λ_0	induced flow velocity
μ	mass per unit length
ξ	column matrix of center of mass offset from the frame of reference origin in $\mathbf{b}_i$ basis
ψ	column matrix of small incremental rotations
Ω	column matrix of cross-sectional angular velocity measures in $\mathbf{B}_i$ basis
$()'$	partial derivative of () with respect to x_1
$\dot{()}$	partial derivative of () with respect to time
$\hat{()}$	nodal variable

High-aspect-ratio flying wings may undergo large deflections, which lead to geometrically nonlinear behavior; see Patil and Hodges (2004). Previous studies by Patil and Hodges (2004, 2006) and Patil et al. (2001) showed the inaccuracy of linear aeroelastic analysis and the importance of nonlinear aeroelastic analysis. NATASHA (Nonlinear Aeroelastic Trim And Stability of High Altitude Long Endurance Aircraft) is the computer program used by Patil and Hodges (2006) and Chang et al. (2008) for this study. It is based on the nonlinear composite beam theory of Hodges (2003), which accommodates the modeling of high-aspect-ratio wings. NATASHA uses the aerodynamic theory of Peters et al. (1995) and assesses aeroelastic stability using the p method. Sotoudeh et al. (2010) presented additional parametric studies using NATASHA primarily for the purposes of verification and validation. However, neither the effects of sweep nor of engine placement were included in these studies. Previous comparisons by Sotoudeh et al. (2010) showed that results from NATASHA are in excellent agreement with well-known beam stability solutions (Timoshenko and Gere, 1961; Simitses and Hodges, 2006), the flutter problem of Goland (1945), experimental data presented by Dowell et al. (1977), and results from well-established computer codes such as DYMORE (Bauchau and Kang, 1993; Bauchau, 1998), and RCAS (Saberi et al., 2004). The behavior of sub- and supercritical eigenvalues was verified by Mardanpour et al. (2013) using the classical cantilever wing model of Goland (1945) and the continuum aerodynamics model of Balakrishnan (2012). In the same work, they studied the suitability of modeling sweep with NATASHA using the same Goland model. For the effect of sweep on divergence they compared results from NATASHA with the approximate formula of Hodges and Pierce (2011), and for flutter they compared results with work done by Lottati (1985). In both cases results were in excellent agreement.

Effects of follower forces on dynamic instability of beams were studied by Beck (1952), Bolotin (1959), Como (1966), Wohlhart (1971), and Feldt and Herrmann (1974). Despite engine thrust being a follower force, few studies included this effect along with aeroelastic effects until the work of Hodges et al. (2002), who presented a case in which the thrust vectors (from massless engines) were placed on the outboard portion of the wings of an aircraft with high aspect ratio wings, thus maximizing thrust effects. They concluded that increasing engine thrust can either stabilize or destabilize, and flutter speed and frequency were highly dependent on the ratio of bending stiffness and torsional stiffness of the wing.

Fazelzadeh et al. (2009) studied the effect of a follower force and mass arbitrarily placed along a long, straight, homogeneous wing. Their results emphasize the effect of follower forces along with the external mass magnitude and