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Wing box transonic-flutter suppression using piezoelectric self-sensing diagonal-link actuators

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ABSTRACT

The main objective of this research is to study the capability of Piezoelectric (PE) self-sensing actuators to suppress the transonic wing-box flutter, which is a flow-structure interaction phenomenon. The unsteady general frequency modified Transonic Small Disturbance (TSD) equation is used to model the transonic flow about the wing. The wing-box structure and the piezoelectric actuators are modeled using the equivalent plate method, which is based on the first-order shear deformation plate theory (FSDPT). The piezoelectric actuators are used as diagonal-links. The optimal electromechanical-coupling conditions between the piezoelectric actuators and the wing are collected from previous work. Three main different control strategies; Linear Quadratic Gaussian (LQG) which combines the Linear Quadratic Regulator (LQR) with the Kalman Filter Estimator (KFE), Optimal Static Output Feedback (SOF), and Classic Feedback Controller (CFC); are studied and compared. The optimum actuators and sensors locations are determined using the Norm of Feedback Control Gains (NFCG) and Norm of Kalman Filter Estimator Gains (NKFEG), respectively. A genetic algorithm (GA) optimization technique is used to calculate the controller and estimator parameters to achieve a target response.

1. Introduction

Flying aircraft in the transonic regime is efficient because of the high lift-to-drag ratio. However, several undesirable phenomena occur in the transonic regime. From an aeroelastic point of view, the major concern is the presence of moving shock waves and rapid changes in the flow because of structural deflections. This flow-structure interaction under certain dynamic pressure leads to a phenomenon known as transonic flutter. Flutter can be defined as the onset of dynamic instability of the wing self-excited vibrations due to the interaction between the wing structure and the flow around the wing. This flutter may cause failure to the wing if not delayed or controlled. Flutter danger prevents flying above certain aerodynamic conditions, so recent research work is concerned with controlling flutter. Using smart materials like embedded or bonded piezoelectric material to the wing may provide proper sensing and damping to wing flutter. Loewy (1997) introduced a complete survey of recent developments in smart structures with aeronautical applications.

Studying the flutter suppression of fixed wings with smart structures is a complicated problem because of complexity of the aerodynamic and structural analyses. Many simplifications can be done in the aerodynamic or structural models. Most researchers simplify the wing to a cantilevered plate, and a few of them model the wing as a wing box structure. Also, most researchers use simplified analytic aerodynamic theories, and a few of them use complicated numerical techniques. Simplified techniques (analytic or numeric) can be found for subsonic and supersonic flow regimes, but the transonic flow regime is more complicated. Although a transonic flow model with a wing box structure is the most realistic flutter model, few researches take this approach.

The primary objectives of this study are: (1) to develop nonlinear equivalent plate tool for analyzing the wing box structure with bonded piezoelectric patches, (2) to develop an unsteady transonic flow solver to predict the flutter condition of the wing, (3) to design a practical control tool that suppresses transonic wing flutter using piezoelectric sensors and actuators, (4) using the genetic algorithm optimization technique to force the wing to track a target response

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Nomenclature

A	area
$\{a_1(x,y) - a_5(x,y)\}$	Ritz function vectors
c, c_r	wing local and reference chords
C_P	pressure coefficients
$[d]$, $\{d\}$	piezoelectric strain matrix and PE strain vector
$\{D_E\}$	electric displacement vector
E_E	electric field
E_o	the Young's modulus
$\{F_{EQ}\}$, $\{F_{EV}\}$	electric forces due to surface charge and electric potential, respectively
$\{F_M\}$	vector of mechanical forces
$h(x,y)$	depth polynomial series
$H(k)$	series coefficient in a depth polynomial series
$[I]$	identity matrix
$[K_{EE}]$	piezoelectric capacitance matrix
$[K_{ME}]$, $[K_{EM}]$	PE electromechanical coupling matrices
$[K_{MM}]$	stiffness matrix
$[M_{MM}]$	mass matrix
M_∞	free stream Mach number
$mh(k)$, $nh(k)$	powers of x and y terms in a depth polynomial series; Eq. (4)
$mrw(k)$	powers of x terms in the polynomial series for rib-web thickness Eq. (4)
$ms(k)$, $ns(k)$	powers of x and y terms in the polynomial series for skin-layer thickness; Eq. (4)
$mu(j)$, $nu(j)$	powers of polynomial terms in the series for $u_o(x,y,t)$
$mv(j)$, $nv(j)$	powers of polynomial terms in the series for $v_o(x,y,t)$
$mw(j)$, $nw(j)$	powers of polynomial terms in the series for $w_o(x,y,t)$
$m\alpha x(j)$, $n\alpha x(j)$	powers of polynomial terms in the series for $\alpha_x(x,y,t)$
$m\alpha y(j)$, $n\alpha y(j)$	powers of polynomial terms in the series for $\alpha_y(x,y,t)$
N_1, N_2, N_3, N_4, N_5	number of generalized displacements in q_1, q_2, q_3, q_4, q_5, respectively
N_h, N_{rw}, N_s, N_{sw}	number of terms in the depth, rib web, skin thickness and spar web series respectively; Eq. (4)
N_u, N_v, N_w, $N_{\alpha x}$, $N_{\alpha y}$	number of terms in Ritz polynomial series for displacement fields
$nsw(k)$	powers of y terms in the polynomial series for spar-web thickness; Eq. (4)
$\{q\}$	total vector of unknown generalized displacements, $\{q\} = \{q_1, \ldots, q_5\}^T$
q_{cr}, q_∞	critical and far field dynamic pressures, respectively
q_1, q_2, q_3, q_4, q_5	generalized displacements vectors
$[Q]$, $[\overline{Q}]$	constitutive matrices
Q_{ch}	surface charge density
t	physical time
$\bar{t}$	non dimensional time, $U_\infty t/c_r$
$t_{rw}(x)$, $t_s(x,y)$, $t_{sw}(y)$	thickness of a layer in a rib web, skin and spar web, respectively
$T_{rw}(k)$, $T_s(k)$, $T_{sw}(k)$	coefficients in the polynomial series for rib web, skin and spar web layer thickness, respectively
U_∞	free stream velocity
u, v, w	displacements in the x, y, and z directions, respectively
u_o, v_o, w_o	x, y, z displacements of a reference surface
V	electric potential
W_M	external work
x, y, z	physical Cartesian coordinates in streamwise, spanwise, and vertical directions, respectively
$\bar{x}, \bar{y}, \bar{z}$	non dimensional coordinates; x/c_r, y/c_r, z/c_r
α_x, α_y	first order-shear rotations about y and x, respectively
$[\alpha^\sigma]$	dielectric permittivity matrix at constant mechanical stress
δ	time variation
$\{\varepsilon\}$	mechanical strain vector
γ	ratio of specific heats
v	Poisson ratio
ρ	material density
$\{\sigma\}$	mechanical stress vector
ω	angular frequency
$\forall$	volume

Subscripts

b	bending component
m	membrane component
$_{,\bar{x}}, _{,\bar{y}}, _{,\bar{z}}, _{,\bar{t}}$	partial derivatives to the non-dimensional coordinates.

Superscripts

a	actuator
s	sensor
T	transposed matrix
$\cdot$	time derivative

which is pre-described by the designer, and (5) determine the optimum locations for the piezoelectric sensors and actuators.

Forster and Yang (1998) examined the use of piezoelectric actuators to control supersonic flutter of wing boxes. Aluminum built-up wing boxes are used to analyze the free-vibration, aeroelastic, and control concepts associated with flutter control. Finite elements are used to calculate deflections caused by input forces, member stresses and strains, natural frequencies, and mode shapes. Linear strip theory with steady aerodynamics is applied to find the frequency coalescence of modes indicating flutter. The variables of interest are the skin, web, and rib thicknesses associated with torsional rigidity, and the spar cap and vertical post areas associated with bending rigidity. Piezoelectric actuators are implemented in a configuration that generates torsional control of the wing box. Pole assignment concepts are applied to change the free-vibration frequencies. A parametric study changing the free-vibration frequencies using piezoelectric actuators is conducted to determine which thicknesses of skins, webs, and ribs will meet a specified flutter requirement. The addition of piezoelectric actuators allows the flutter requirements to be met at smaller thicknesses of skins, webs, and ribs, so that the overall weight of the wing box, including actuators, is decreased.

Sanda and Takahashi (1998) carried out tests and analysis of flutter and vibration control of a rectangular aluminum plate wing in a wind tunnel with subsonic flow. The plate wing was driven by eight piezoceramic actuators bonded on the surfaces at the wing root. The acceleration sensor was located at the wing tip, and the signal was sent to a digital signal processor through filters, and the control signal was sent to the power amplifier. Vibration-control test results showed that the Structural Damping Ratio (SDR) of the system increases remarkably using both gain control and reduced Linear Quadratic Gaussian (LQG) control. Using gain control, the SDR increased up to 0.3. Wind-tunnel tests for flutter control showed that flutter speed increased about 2.9 m/s using a reduced LQG controller.