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Panel flutter prediction in two dimensional flow with enhanced piston theory

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ABSTRACT

Piston theory may be used in the high Mach number supersonic flow region and/or in very high frequency subsonic or supersonic flow. In this flow model, the pressure at a point on the fluid-solid interface only depends on the downwash at the same point. However the classical piston theory may not be sufficient for some phenomena in aeroelasticity and aeroacoustics (far field prediction). Dowell and Bliss have created an extension of piston theory that allows for higher order effects that take into account the effect the distribution of downwash on pressure at any point. For simple harmonic motion, expansions in reduced frequency, inverse reduced frequency and/or inverse (square of) Mach number have all been created; The effects of higher order terms in these several expansion in creating an enhanced piston theory was illustrated for plunge and pitch motion of an airfoil (discrete system) by Ganji and Dowell. In the present paper, flutter prediction for a flexible panel in two –dimensional flow is investigated using enhanced piston theory. The goal of the present paper is to demonstrate that an enhance version of piston theory can analyze single degree of freedom flutter of a panel as compared to the classical piston theory and quasi-steady aerodynamic models which can only treat coupled mode flutter.

1. Introduction

Piston theory is very useful in some aeroelastic applications in supersonic and hypersonic flow as suggested by Lighthill (1953). Following Lighthill, piston theory was developed as an unsteady aerodynamic model for the aeroelastician by (Ashley and Zartarian, 1956), and it has continued to be important to the aeroelasticity practitioner and researcher alike, e.g., see papers by (Liu et al., 1997; Mei et al., 1999; Friedmann et al., 2004). (Dowell, 1966; Xie et al., 2014a, 2014b). These investigators as well as others have used this model in many studies in panel flutter and limit cycle oscillations (LCO) including chaos and other nonlinear dynamic phenomenon. Recently, (Zhang et al., 2009) have demonstrated how one may extend piston theory by using local mean steady flow properties in place of their freestream counterparts. However, piston theory is not adequate for lower supersonic Mach numbers and especially for $1 < M < \sqrt{2}$. For this reason, (Dowell and Bliss, 2013) created an "*enhanced piston theory*" that is obtained from an expansion in powers of reduced frequency in Laplace/Fourier space. An algebraic error in their paper has been corrected by (Dowell and Ganji, 2015).

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Nomenclature

$M = U_\infty / a_\infty$	Mach number
U_∞	freestream velocity
a_∞	free stream speed of sound
a	panel chord
ω	frequency in rad/sec
ρ_∞	free stream fluid density
$\bar{\Delta}P = \overline{p} - p_\infty$	aerodynamic pressure loading on panel
$q = \rho_\infty U_\infty^2 / 2$	dynamic pressure
$\beta = \sqrt{M^2 - 1}$	compressibility correction factor
$\tau = \overline{\omega}_0 t$	nondimensional time
$\overline{\omega}_0 = \sqrt{D/ma^4}$	nondimensional frequency
D	plate stiffness
$\phi_i(x)$	mode function
$q_i(t)$	generalized coordinates
x	stream wise coordinates
m	panel mass
$\lambda = 2qa^3/D$	nondimensional dynamic pressure
t	time
T	kinetic energy
U_B	bending elastic energy
w	panel transverse deflection
Q_i	generalized aerodynamic force
$\mathcal{L}$	Lagrangian
C_i	aerodynamic model coefficient

In the Mach number range, $(1 < M < \sqrt{2})$, the low frequency expansion of the full potential flow theory cannot predict the flutter boundary and post-flutter behavior because the damping predicted is always negative and the aeroelastic system is always unstable according to this aerodynamic model. By expanding the solution to higher powers of reduced frequency the theory can predict the change in sign of the aerodynamic damping as a function of reduced frequency (Ganji and Dowell, 2016) and hence the flutter boundary and the post flutter behavior. This new aerodynamic theory previously published and is used here to predict the flutter boundary.

The vast majority of papers published on panel flutter use the classical form of piston theory or the lowest frequency expansion of potential flow theory. This effectively limits the physical fidelity of the results to high supersonic Mach numbers, certainly greater than the $\sqrt{2}$ and more conservatively to Mach numbers greater than 2. However the lower supersonic Mach number range is usually the most critical for assessing the flutter of a panel, i.e. $M < \sqrt{2}$). The present paper demonstrates that an enhancement of the classical low reduced frequency expansion is possible that provides meaningful physical results in the lower supersonic Mach number range while not unduly complicating the aerodynamic model.

Using a reduced frequency expansion is not new idea; many years ago, (Nelson et al., 1954) used a similar expansion for obtaining lift and moment for plunge and pitch motions of an airfoil. (Dowell and Bliss, 2013) have used Laplace transforms methods and dealt directly with the pressure distribution for arbitrary spatial downwash (airfoil motions). In their extension to piston theory, higher powers of frequency appear and the pressure depends the structural surface motion at all points on the airfoil; in particular they observed single degree of freedom flutter for a pitching airfoil due to negative aerodynamic damping when $M < \sqrt{2}$. Subsequently (Ganji and Dowell, 2016), investigated the effects of higher order terms in these expansions on the convergence of the expansion.

For a readable history of panel flutter analysis including the distinction between single mode and multi-mode flutter the paper by Shishaeva et al. (2015) is highly recommended. These authors use a computational fluid dynamics (CFD) model to address the single mode flutter problem and note that classical piston theory is not capable of treating this physical phenomenon. The present enhanced piston theory aerodynamic model does allow single mode flutter to be considered and represents an intermediate model between classical piston theory and a CFD model. Enhanced piston theory is more

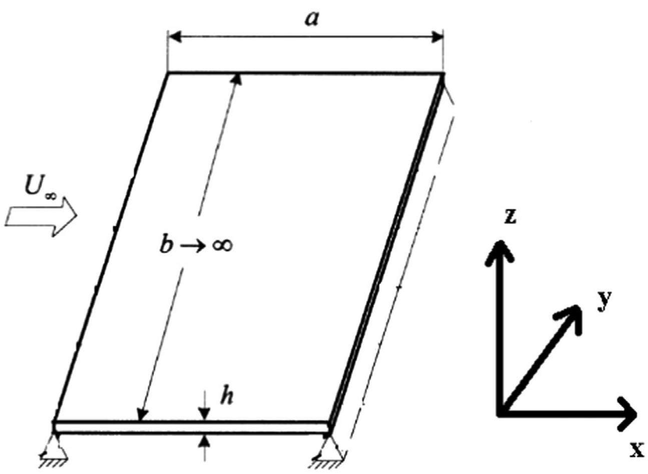

Fig. 1. Schematic diagram of a two-dimensional panel (Beloiu et al., 2005).