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Aeroelastic stability of a cantilevered plate in yawed subsonic flow

S. Chad Gibbs, Anosh Sethna, Ivan Wang, Deman Tang, Earl Dowell

Duke University, Durham, NC 27708, USA

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ABSTRACT

The aeroelastic stability of cantilevered plates with their clamped edge oriented both parallel and normal to subsonic flow is a classical fluid–structure interaction problem. When the clamped edge is parallel to the flow the system loses stability in a coupled bending and torsion motion known as wing flutter. When the clamped edge is normal to the flow the instability is exclusively bending and is referred to as flapping flag flutter. This paper explores the stability of plates during the transition between these classic aeroelastic configurations. The aeroelastic model couples a classical beam structural model to a three-dimensional vortex lattice aerodynamic model. The aeroelastic stability is evaluated in the frequency domain and the flutter boundary is presented as the plate is rotated from the flapping flag to the wing configuration. The transition between the flag-like and wing-like instability is often abrupt and the yaw angle of the flow for the transition is dependent on the relative spacing of the first torsion and second bending natural frequencies. This paper also includes ground vibration and aeroelastic experiments carried out in the Duke University Wind Tunnel that confirm the theoretical predictions.

1. Introduction

The interaction between a cantilevered elastic plate and a uniform axial flow is a canonical fluid–structure interaction problem. If the flow is oriented *parallel* to the clamped leading edge the system is described as a wing-like configuration. If the flow is oriented *normal* to the clamped edge then the system is referred to as flag-like. There is extensive research on the aeroelastic stability of the wing-like configuration due to the similarities between the simple cantilevered beam and aircraft wings. Researchers have been interested in the stability of aircraft wings since a 1916 flutter incident on a Handley Page O/400 twin engine biplane bomber (Garrick and Reed, 1981; Kehoe, 1995). Wing-like aeroelastic systems typically lose stability due to a coalescence between a bending and torsion mode. The simplest aeroelastic models for a wing are typical section models that include just a single degree of freedom each in plunge and twist (Dowell et al., 2004). Goland (1945) is the classic paper describing the coupled bending torsion flutter of a simple cantilever beam in the wing configuration. Of particular interest to the current research are aeroelastic studies of swept wings. Bisplinghoff et al. (1996) contains a review of the classic literature relating to the aeroelastic stability of swept wings. These authors note that modeling a swept wing is particularly challenging due to the misalignment between the normal to the pitching axis and the incoming flow.

The present study differs from the classic explorations of the swept wing due to the application of the clamped boundary condition. For a traditional swept wing configuration the clamp is applied parallel to the flow, changing the shape of the structure for every angle. For the current study the clamped edge is rotated with the structure. This is similar to the rotated wing experiments conducted by Barmby et al. (1951). In their study, the authors look at the flutter characteristics of a wing

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Nomenclature

EI	beam bending stiffness
GJ	beam torsional stiffness
h	plate thickness
k_m	beam radius of gyration
L	plate chord length in the x' direction
m	mass per unit length ($\rho_s hS$)
N,M	number of structural modes included in bending and twist
$P_i^{n+1/2}$	aerodynamic force on the i'th panel at a time step between n and $n+1$
S	plate span length in the y' direction
S_c, S_s	aerodynamic mesh elements in the chord and span direction
$V_{d,i}$	z component of the velocity of the panel at the i'th colocation point
$w(x',t)$	bending displacement
x', y'	normal to fixed edge and parallel to fixed edge structural coordinates
x, y	streamwise and normal to the flow aerodynamic coordinates
β	yaw angle from the flapping flag configuration
Γ_i^n	i'th circulation strength at time step n
ρ_a, ρ_s	fluid and structure material density
$\phi(x',t)$	beam rotation around the elastic axis

that is rotated up to 60°. The current work extends this research to explore the rotated wing all the way to the second classic fluid structure interaction problem for a clamped-free elastic plate.

It is well known that the flag-like cantilever exhibits a bending only flutter instability in low subsonic flow as the free stream velocity is increased above a critical velocity. Typically the instability is caused by the coalescence of the two lowest frequency bending modes for the mass ratios explored in this paper (Doaré et al., 2011; Eloy et al., 2007, 2008; Gibbs et al., 2012; Tang et al., 2003). Since the experimental observations of the flapping flag by Taneda (1968) and Kornecki et al. (1976), many scholars have explored the stability of this system experimentally and theoretically. In addition to the problem's inherent physical significance, Doaré and Michelin (2011), Dunnmon et al. (2011) and Giacomello and Porfiri (2011) have recently proposed using the phenomena for energy harvesting applications and Eloy and Schouveiler (2011) and Hellum et al. (2011) have explored the potential of using flutter for propulsion. Furthermore, Balint and Lucey (2005), Huang (1995) and Howell et al. (2009) have shown that cantilevered plate flutter in the human soft palate can explain snoring and Watanabe et al. (2002) have explored this type of flutter in the printing industry.

The current research focuses on exploring the transition from a flapping flag flutter to wing-like flutter of a cantilever beam as the angle between the clamped edge and free stream velocity changes. In particular this paper presents a linear theoretical model for the rotated aeroelastic system. We create the aeroelastic model by coupling a classic linear beam structural model with a rotated vortex lattice model. We validate the theoretical predictions with aeroelastic experiments conducted in the Duke University Wind Tunnel. This paper explores three distinct configurations that show markedly different transition behaviors from wing flutter to flapping flag flutter.

For the most slender structure we observe an abrupt transition from wing-like flutter to flag-like flutter at an angle near the wing-configuration. The importance of the second bending mode in this instability so near the wing configuration implies that a simplified wing model with only a single bending and a single torsion mode may not completely model the wing instability if the wing is placed in a yawed flow. For the least slender structure we observe a large change in response near the flag configuration. This transition could seriously impact the proposed energy harvesting applications for the flapping flag, causing energy harvesting systems based on the flapping flag to under-produce power. By exploring the transition between two classic aeroelastic systems we are able to describe the way the bending-only flutter for the flag-like system becomes the coupled bending–torsion instability for a wing-like system simply by changing the angle of the incoming flow.

2. Theoretical model

2.1. Beam structural model

We build the model of the aeroelastic system by coupling a classic linear structural model of a beam in bending and torsion to a vortex lattice aerodynamic model. The derivation of the classical structural model can be found in the literature (e.g. Dowell et al., 2004). Fig. 1 shows a schematic of the beam in bending and torsion. The governing equations of motion for the beam are derived from Hamilton's principle:

$$0=\int_0^L [GJ\phi'\delta\phi' + mk_m^2\ddot{\phi}\delta\phi - M_\phi\delta\phi + EIw''\delta\overline{w}'' + m\ddot{w}\delta w - L_w\delta w]\, dx'. \tag{1}$$

We solve Eq. (1) using a classic Rayleigh–Ritz approach. We assume a modal expansion for the bending and torsion degrees of freedom where the assumed mode shapes, $g_n(x')$ and $h_n(x')$, satisfy the geometric boundary conditions, in this case clamped-free. The modal expansion is given by the following expression:

$$w(x',t)=\sum_n^N q_n(t)g_n(x'), \phi(x',t)=\sum_m^M q_m(t)h_n(x'). \tag{2}$$

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