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Nonlinear single-mode and multi-mode panel flutter oscillations at low supersonic speeds

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ABSTRACT

In this study we numerically analyse nonlinear flutter oscillations of elastic plate in a gas flow. In contrast to many other studies, we use inviscid flow model instead of piston theory or other simplified aerodynamic theories. This study aims to investigate the region of low supersonic Mach numbers, $1 < M < 2$, where several plate eigenmodes can be simultaneously unstable, and resulting oscillations are governed by nonlinear interaction of growing modes. Three types of unstable plate behaviour have been obtained. First, at $0.76 < M < 1$, the plate diverges. Second, at $1 < M \leq 1.67$, single-mode flutter occurs in three distinct forms: limit cycle in the first mode ($1 < M < 1.33$ and $1.5 < M \leq 1.67$) or higher modes; limit cycle in the first and second modes being in internal 1:2 resonance ($1.12 < M < 1.33$ and $1.42 < M < 1.5$); and non-periodic oscillations with several dominating frequencies being in more complex ratio ($1.33 < M < 1.42$). Third, at $M = 1.82$ and increased dynamic pressure, coupled-mode flutter appears. Amplitudes and spectra of each limit cycle type are analysed. The role of aerodynamic nonlinearity in the formation of limit cycle oscillations is discussed.

1. Introduction

Aeroelastic instability of plates in a gas flow has been investigated in numerous studies in the context of the panel flutter problem (Movchan, 1957; Bolotin, 1963; Grigolyuk et al., 1965; Dugundji, 1966; Dowell, 1974; Mei et al., 1999). In the case of subsonic flow, the primary instability type is static divergence, whereas in supersonic flow, instability has an oscillatory nature, i.e., the plate flutters. Flutter instability, in turn, can be either coupled- or single-mode flutter. The first one occurs because of coalescence of the plate eigenfrequencies caused by the action of the flow; it has been studied in detail in the 1950s to 1970s using aerodynamic piston theory. The other flutter type, single-mode flutter, occurs at lower Mach numbers, $1 < M < 2$. Recently, detailed investigation of linear single-mode flutter boundaries has been conducted (Vedeneev, 2005, 2012, 2013a); also, this flutter type has been observed in experiments by Vedeneev et al. (2010). The unusual result that has been obtained is that there is a range of Mach numbers and plate lengths where several plate eigenmodes are simultaneously unstable. Hence, the development of initial perturbation consisting of those modes and formation of the limit cycle is governed by nonlinear interaction of the unstable eigenmodes.

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In this study, aeroelastic instability of a plate in an airflow is investigated by direct time-domain numerical simulation. Plate and gas flow motions are modelled in solid and fluid codes, respectively, with direct coupling between them. The effect of the boundary layer over the plate is neglected. The main goal of this study is to investigate the nonlinear development of growing oscillations in case of several linearly growing eigenmodes.

Several time-domain simulations of nonlinear panel flutter were performed at conditions of transonic and low supersonic speeds by different authors (Bendiksen and Davis, 1995; Gordnier and Visbal, 2002; Hashimoto et al., 2009; Alder, 2015). Their studies showed that limit cycle oscillations resulting from single-mode linear growth mechanism occur in the form of travelling wave with dominating first-mode shape. In the present study, we show that there is a range of Mach numbers where such a limit cycle is not unique, and the other limit cycle includes two first modes being in 1:2 internal resonance. For higher Mach numbers, where higher eigenmodes become unstable, high-frequency limit cycles and non-periodic oscillations occur. Such high-frequency oscillations, occurring on an aircraft panel, yield much faster fatigue damage than the first-mode limit cycle or conventional coupled-mode flutter oscillations.

In contrast to other panel flutter studies, we consider two problem formulations: air flowing over one side of the panel and over two sides with twice lower air density. When linearising, these formulations become identical, such that the difference in the nonlinear problem represents the effect of aerodynamic nonlinearity. We show that in all cases, except a very narrow vicinity of $M=1$, the results obtained from both formulations are similar, i.e., all limit cycle oscillations observed are caused by structural nonlinearity only, whereas the aerodynamic nonlinearity is negligible.

2. Formulation of the problem

We investigate two-dimensional motion of an elastic plate in a uniform airflow . The air flows over one or two sides of the plate. In the first case, the pressure underneath the plate equals the free-stream pressure; in the latter case, the flow parameters along both sides of the plate are equal. The unperturbed state of the plate is flat.

The flow over one side of the plate represents the classical panel flutter model. The two-sided flow is studied to reveal the role of aerodynamic nonlinearity in limit cycle oscillations, as will be discussed below.

2.1. Plate model

The elastic plate of length $L_p = 0.3$ m and thickness $h_p = 0.001$ m is clamped at both edges ($w(x,t) = \partial w(x,t)/\partial x = 0$), where it smoothly passes into a rigid surface (Fig. 1). The plate is made of steel with Young's modulus $E = 2 \times 10^{11}$ Pa, Poisson's coefficient $\nu = 0.3$, and density $\rho_m = 7800$ kg/m^3. In dimensionless terms, the plate stiffness and length are

$$D = \frac{D_p}{a^2 \rho_m h^3} = 21.4, \quad L = \frac{L_p}{h_p} = 300, \tag{1}$$

where $D_p = Eh^3/(12(1-\nu^2))$ is the dimensional plate stiffness, and $a = 331$ m/s is the speed of sound in the air. Similar values of dimensionless parameters correspond to other metal materials (e.g., aluminium and titanium). The plate is governed by the nonlinear Mindlin plate model, where elastic strains are calculated through Koiter–Sanders shell theory.

During a short initial time range $t = 0\ldots\varepsilon$, where $\varepsilon = 0.0002$ s, a slight disturbing force is applied to the panel to introduce initial perturbation of the system. At $t > \varepsilon$, no external force is applied to the plate and the flow so that the subsequent behaviour of the system is governed by the fluid–structure interaction only.

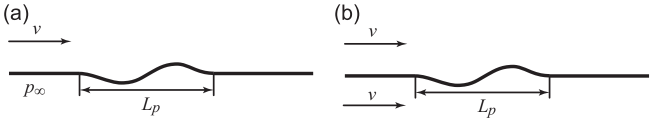

Fig. 1. Plate in a gas flow: one-sided (a), two-sided (b) flow.

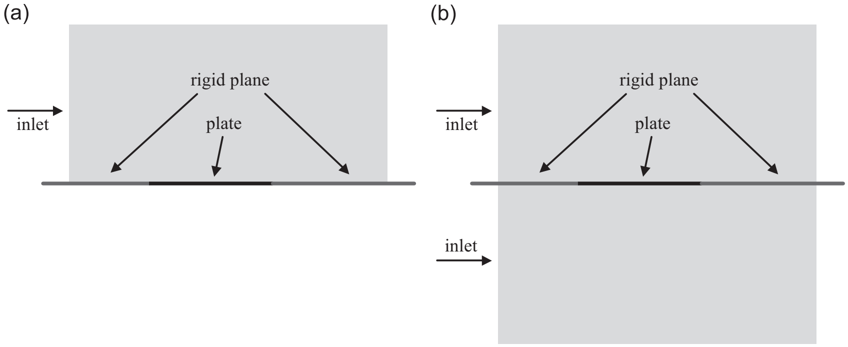

Fig. 2. Simulation domain: one-sided (a), two-sided (b) flow.