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Numerical investigation of the effects of compressibility on the flutter of a cantilevered plate in an inviscid, subsonic, open flow

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ABSTRACT

We have carried out a numerical study of the influence of the upstream Mach number on the flutter of a two-dimensional, cantilevered, flexible plate subject to a subsonic, inviscid, open flow. We have assumed a linear elastic model for the plate and that the fluid flow is governed by the linearized potential theory. The fluid equations are solved with a novel frequency-domain, finite differences method to obtain the generalized aerodynamic forces as a function of the plate displacements. Then, these generalized forces are coupled to the equation of motion of the plate and an eigenvalue analysis is performed to find the flutter point. The obtained results are in good agreement with those of related theoretical and experimental studies found in the literature. To the best of our knowledge, the analysis performed here is the first self-consistent, parametric study of the influence of the compressibility on the flutter point of a two-dimensional cantilevered plate in subsonic flow.

1. Introduction

The flutter of a cantilevered plate is an example of fluid-structure interaction that has received great attention in the literature –e.g., in the monographs by Dowell [1] and Païdoussis [2]–, since it helps to understand many aeroelastic phenomena such as aircraft wing flutter [3], train panel flutter [4], energy harvesting [5,6], human snoring [7] and paper web instability [8]. However, as we briefly review next, the major part of the results found in the literature are restricted to incompressible flows, whereas the effect of the compressibility –that may not be negligible in cases such as aircraft wing flutter or train panel flutter, among others– seems to have received little attention.

Such a lack of attention may be due to the fact that it is more difficult to obtain a direct relationship between aerodynamic loads over the plate and its motion when the flow is compressible. In effect, in the incompressible case, the numerical modelling of the flutter phenomenon has been traditionally approached by coupling the equation of motion of the plate to an appropriate aerodynamic model that provides the unsteady fluid pressures over the plate given its motion. Some of these aerodynamic models are based on theoretical relations [9,10] obtained by Theodorsen [11] and Küssner and Schwartz [12] for unsteady, linearized, incompressible flows, as is done, for example, in the papers of Kornecki [13,14], Huang [7], Guo and Païdoussis [15], Eloy et al. [16,17], Li et al. [18–20] and Drazumeric et al. [21]. However, this procedure cannot be extended to

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linearized, compressible flows because, in this case, the relation between aerodynamic forces and the airfoil motion is governed by the more complicated Possio's equation, for which no analytical solution is known, but only an approximated one [22].

Some other aerodynamic models are based on incompressible vortex-lattice methods, as happens in the works of Yamaguchi et al. [23], D. Tang et al. [3], Argentina and Mahadevan [24], L. Tang and Païdoussis [25,26], L. Tang et al. [5,27], Gibbs et al. [28], Zhao et al. [29], Howell and Lucey [30,31], Alben [32], and Michelin and Llewellyn Smith [33]. Although these methods have been widely used in unsteady, incompressible aerodynamics –see, for example [34],–, they present some inconveniences when extended to compressible flows [35,36] such as: (i) they are based on a fundamental solution –the so-called *unsteady compressible vortex*– whose velocity field is not well-known and lacks a clear physical meaning [37], (ii) when formulated in the time domain, they have to keep track of the history of the vortices' intensities in order to compute the pressure jumps at the airfoil at a given instant and (iii) their extension to three-dimensional flow is not clear, although some efforts have been done on the matter [38]. These drawbacks, which may also appear when using other kind of fundamental solutions, such as dipoles [39], or other boundary elements methods in general [40], considerably complicate the extension of the analysis of the incompressible flutter problem –usually performed using eigenvalue theory [30,31] or time-domain simulations [3,35,36]– to the compressible case.

An alternative way to obtain the aerodynamic pressures over the plate given its motion is to directly solve the Navier-Stokes equations, as has been done by Watanabe et al. [8], Balint and Lucey [41], Khalili et al. [42] and Cisonni et al. [43]. Some of these authors [8,42] have even considered compressibility effects for the case of very small Mach numbers, but their methods have proved to be too expensive compared to those based on potential flow theory [8]. Therefore, in order to deal with compressibility effects at higher Mach numbers, some investigators have tried an approach based on the direct discretization in space and in time of the linearized, compressible, potential flow equations. This is done, for example, in the works of Huang and Zhang [44] –who formulated a Chebyshev pseudospectral method– and of Colera and Pérez-Saborid [35,36] –who employed finite differences–. However, only the latter authors effectively applied their method to compressible flows –since Huang and Zhang only considered the case of zero Mach number–. Finally, we should also mention the differential quadrature method developed by Li and Yang [4] to analyse the dynamics of panels wetted by one side in a compressible stream with the simplifying assumption that the incident flow remains unperturbed at the stations corresponding to the border of attack and to the trailing edge of the panel, respectively.

Compressibility effects on the flutter of a cantilevered, two-dimensional plate in a compressible, subsonic flow have been previously studied by Tanida [45] –who developed a compressible doublet-lattice method in the frequency domain for a plate in channel flow, but used only one Galerkin mode to describe its motion– and by Colera and Pérez-Saborid –who used first a compressible vortex-lattice method [37,46,47] and later a finite differences method [35,36] to study a single case of a plate of given mass and stiffness–. The aim of this work is to generalize these investigations by performing a parametric study of the flutter speed and the flutter frequency of a two-dimensional, cantilevered plate in a compressible, subsonic flow as a function of its mechanical properties and the upstream Mach number. For that purpose, we have developed a numerical method based on expressing the plate equations of motion in terms of shape functions and generalized coordinates and on solving the equations for the linearized potential flow with a novel frequency-domain numerical scheme adapted from that presented in Refs. [35,36].

The paper is structured as follows. First, the equations of motion of the plate are introduced in section 2. Then, a frequency-domain, finite differences method that provides the generalized aerodynamic forces is described and validated in section 3. The computation of the flutter curves of the plate is explained in section 4, whereas the results are discussed in section 5. Finally, some conclusions and future developments are pointed out in section 6.

2. Dynamic model of the plate

Consider the cantilevered flexible flat plate shown in Fig. 1. Let the incident flow –of density ρ_∞, speed U_∞ and Mach number M_∞– come in the x direction, along which the plate has a length L, and let the dimension along the z-axis, H, tend to infinity in order to simulate a two-dimensional problem in the x-y plane.

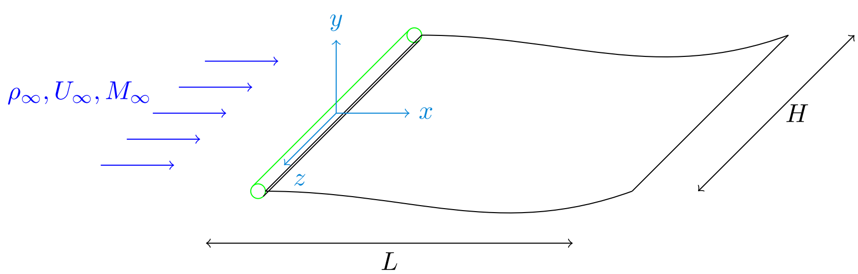

Fig. 1. Scheme of a cantilevered flexible plate subject to an incident flow.