Journal of Fluids and Structures 78 (2018) 331–342

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Stability analysis of rectangular parallel plates interacting with internal fluid flow and external supersonic gas flow

S.A. Bochkarev *, S.V. Lekomtsev

Institute of Continuous Media Mechanics RAS, Acad. Korolev Str. 1, Perm, 614013, Russian Federation

HIGHLIGHTS

- Aero- and hydro-elastic stability of a plates (or an assembly of plates) is examined.
- Numerical simulation is based on the finite-element algorithm.
- Stability diagrams for plates with different boundary conditions are obtained.
- External supersonic gas flow can produce both the stabilizing and destabilizing effect.

ARTICLE INFO

Article history:
Received 8 June 2017
Received in revised form 23 November 2017
Accepted 18 January 2018

Keywords:
Aeroelasticity
Supersonic gas flow
Potential flow of compressible fluid
Rectangular plates
Finite element method
Stability
Flutter

ABSTRACT

In this paper, we analyze the dynamic stability of deformable rectangular plates (single and two parallel) that interact simultaneously with the external supersonic gas flow and the internal flow of an ideal fluid. The mathematical formulation of the dynamics of elastic structures is made using the variational principle of virtual displacements, which includes the expression for the work done by aero- and hydro-dynamic forces. The motion of the liquid in the case of small perturbations is described by the equations of potential theory, which are converted to a weak form using the Bubnov–Galerkin method. Numerical solution of the problem is based on the application of the procedures of the finite element method to the coupled system of equations. The estimation of stability involves computation and analysis of complex eigenvalues, obtained at gradually growing velocity of the fluid or gas flow. The diagrams showing the mutual influence of fluid and gas flow velocities on the boundary of aero-hydroelastic stability, are constructed and the effects of the kinematic boundary conditions specified at the edges of the structure and the height of the fluid layer are evaluated. It has been established that the violation of smoothness of the obtained dependences and stability diagrams can be attributed either to a change in the vibration mode, or to a change in the type of stability loss.

1. Introduction

The extensive theoretical and experimental studies (Dowell and Voss, 1965; Dixon, 1966; Dowell, 1975; Vedeneev et al., 2010; Algazin and Kijko, 2015) made over the last few decades have contributed much to gaining in-depth knowledge on the dynamic processes occurring in thin plates in a gas flow. The latest achievements in studying the loss of stability in structures interacting with a fluid or gas flow at the flow velocity exceeding a threshold value are directly related to the derivation of the analytical expression for aerodynamic pressure (Iliushin, 1956; Ashley and Zartarian, 1956; Dowell, 1975)

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* Corresponding author.
E-mail addresses: bochkarev@icmm.ru (S.A. Bochkarev), lekomtsev@icmm.ru (S.V. Lekomtsev).

https://doi.org/10.1016/j.jfluidstructs.2018.01.009
0889-9746/

based on the piston theory. Today, such an approach is actually a major research tool for studying the phenomenon of panel flutter in the case of a supersonic flow, including simulation, which is based on the finite-element method (FEM) (Olson, 1967; Olson, 1970; Sander et al., 1973; Bismarck-Nasr, 1992). For the subsonic flows of gas, its behavior is more correctly described by the potential theory. The obtained results have shown that the type of instability is determined not only by the flow parameters, but also by the kinematic boundary conditions specified at the plate ends. It has been found (Kornecki et al., 1976; Païdoussis, 2014) that simply supported and clamped–clamped plates lose their stability in the form of divergence in the subsonic gas flow and in the form of flutter in the supersonic flow. In the case of a single-sided support (cantilever), the flutter-type instability occurs. Background information concerning the history and nature of this phenomenon is described in detail in the monograph of Païdoussis (2014). A new approach to exploration of the aeroelastic stability of a cantilevered plate, interacting with a potential incompressible gas flow, is proposed in Avramov (2016) and Avramov et al. (2017). The key idea behind the method is to express a pressure drop on the surface of the plate in terms of hypersingular integral equations with respect to aerodynamic derivatives. The determined critical velocities are compared with the numerical solutions, which were obtained with a set of ANSYS packages (Fluent and ANSYS Mechanical). The flutter instability of one and several simply supported, interconnected plates is considered in a three-dimensional formulation in Shitov and Vedeneev (2017). In this work the stability boundaries are obtained for different Mach numbers and aspect ratios of the plates. The aerodynamic pressure is determined by solving the linearized equations of the potential flow theory together with the boundary conditions at infinity, using the Laplace transformations. The numerical procedure for evaluating eigenvalues is based on the Bubnov–Galerkin method and is a generalization of the previously developed method to a three-dimensional case (Vedeneev, 2012).

The retention of nonlinear terms in the stress–strain relations allows a more accurate simulation of large-amplitude vibrations accompanied the flutter phenomenon (Dowell, 1966, 1967; Mei, 1977; Yang and Han, 1983; Haddadpour et al., 2007). In Mei (1977) and Yang and Han (1983), the nonlinear eigenvalue problem is reduced to a sequence of linear problems by applying an iterative algorithm, which is based on the construction of eigenmodes. The aeroelastic stability of plates made of functionally-graded and composite materials is considered in Prakash and Ganapathi (2006), Haddadpour et al. (2007), and Rossettos and Tong (1974). In papers Prakash and Ganapathi (2006) and Haddadpour et al. (2007), the effect of the volume fraction index on the critical value of dynamic gas pressure was investigated. The solution of the nonlinear problem (Haddadpour et al., 2007) demonstrates that functionally-graded materials strongly affect the behavior of structures in the supercritical zone. In Prakash and Ganapathi (2006), it was shown that temperature heating of a structure leads to a decrease in the critical velocities, at which flutter occurs. The analysis of anisotropic plates made in Rossettos and Tong (1974) showed that the nonmonotonic dependence of the eigenfrequencies on the filament angle leads to a similar qualitative change in the critical value of aerodynamic pressure.

Investigations of plates interacting with a flowing fluid also have half-century-old history. This phenomenon has been the focus of numerous numerical–analytical investigations, from the analysis of the behavior of infinite and semi-infinite plates to the analysis of finite-dimensional spatial structures. A historical review of the research methods and models is given in the papers by Bochkarev et al. (2016), Bochkarev and Lekomtsev (2016a) and in the monograph of Païdoussis (2014). In Shoele and Mittal (2016), an analytical approach was proposed to solve the flutter problem for an elastic plate in a two-dimensional channel with a flowing inviscid fluid. In this study the authors developed the ideas, which were set forth by Alben (2008), and modeled of the vortex sheet of the plate wake using the method of images and new Green functions. The system stability is investigated when solving a nonlinear eigenvalue problem. The obtained results have demonstrated that a non-symmetric location of a structure in the channel has a destabilizing effect on the heavy plates. The calculated stability boundary agrees well with the numerical solution of a fully coupled hydroelasticity problem on the basis of the Navier–Stokes equation, which was earlier solved by the above authors using the finite difference method (Shoele and Mittal, 2014). A three-dimensional formulation of the hydroelastic problem of a plate and its solution by the finite element method are considered in Bochkarev et al. (2016), Bochkarev and Lekomtsev (2016a), and Kerboua et al. (2008). In these work the critical velocities for the onset of instability are investigated in relation to several variants of kinematic boundary conditions specified at the ends of a single plate (Bochkarev et al., 2016; Kerboua et al., 2008) or a component of the plate assembly (Bochkarev and Lekomtsev, 2016a; Kerboua et al., 2008). In Bochkarev et al. (2016), the authors also introduce a computational scheme, in which the fluid in the direction of the flow is not restricted to the plate dimensions. The obtained results have indicated that for the variants of boundary conditions considered the assumption of finiteness of the fluid volume leads to slightly reduced values of the critical velocity for the occurrence of divergence and slightly increased velocity values for the occurrence of flutter. The aero- and hydro-elastic stability of a plate located on elastic foundation is studied in Tan et al. (2013). It is shown that the localized increase in rigidity, for example, in the central part of the plate, is an effective means of increasing the stability boundaries. For certain configurations, an increase in rigidity makes it possible to influence the type of the secondary loss of stability.

The behavior of a plate placed in a channel with rigid walls is often analyzed in the framework of the Euler–Bernoulli beam theory (Balint and Lucey, 2005; Tang and Païdoussis, 2007; Howell et al., 2009; Howell and Lucey, 2015; Cisonni et al., 2017). In this case, a two-dimensional flow is described either by the Navier–Stokes equation (Balint and Lucey, 2005; Cisonni et al., 2017), or the vortex method (Tang and Païdoussis, 2007; Howell et al., 2009). The stability of a cantilevered plate in a viscous air flow between two rigid walls was analyzed in Balint and Lucey (2005) and Howell and Lucey (2015). In Balint and Lucey (2005), the authors considered a simplified model of the human airway system and showed that there might exist two types of instability: flutter and divergence. Flutter occurs when the air flow takes place simultaneously in the upper and lower respiratory tracks, while divergence is initiated by the flow in only one of the tracks. A detailed parametric