Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Investigation of a flutter of structures in gas flows with using energy method

To cite this article: F Abdukhakimov and V Vedeneev 2018 *J. Phys.: Conf. Ser.* **1129** 012001

Investigation of a flutter of structures in gas flows with using energy method

F Abdukhakimov[1], V Vedeneev[2]

[1]Lomonosov Moscow State University, GSP-1, Leninskie Gory, Moscow 119991, Russian Federation
[2]Institute of Mechanics of Lomonosov Moscow State University, 1 Michurinsky prosp., Moscow 119192, Russian Federation

E-mail: farruh.abduhakimov7@gmail.com

Abstract. Single-mode flutter is a type of panel flutter occurring at transonic and low supersonic speeds. Transition to instability in the form of single-mode flutter occurs without interaction between natural modes, in contrast to coupled-mode flutter, where coupling between the 1st and 2nd eigenmodes takes place. Blade flutter is one of the main issues that engine designers have to face. The danger of this phenomenon is a rapid increase of blades stresses, which can lead to their destruction. In this paper, a single-mode flutter of panels of rectangle and parallelogram panels and the influence of various design parameters on blade flutter boundary are investigated with using the energy method. It is shown that for parallelogram plates even at a small skew angle the aeroelastic stability increases significantly at transonic and low supersonic flight speeds. The study of blade flutter showed that effect of the inter-blade tension in the mid-span shroud on the flutter is significant in contrast to other investigated parameters.

1. Introduction

Flutter is a dynamic instability of an elastic structure in a fluid flow [1]. This phenomenon occurs in various systems in both mechanical (airplane wing, skin panels, compressor blades and bridges) and biological (blood vessel wall).

Panel flutter is a phenomenon of the stability loss and intensive vibrations of aircraft skin panels appearing under the action of the air flow at high flight speeds. Usually, panel flutter does not lead to the immediate destruction of the aircraft, but it can lead to the accumulation of fatigue damage in the panels [2]. There are two types of panel flutter. The first one is coupled-mode flutter, which is due to the interaction of two oscillation eigenmodes. This type of panel flutter has been studied in detail using the piston theory. The second type is single-mode flutter. In this case, coalescence of the eigenfrequencies and a significant change in the oscillation form do not take place. Single-mode flutter arises at low supersonic speed, where the piston theory is inapplicable. Therefore, it is necessary to use more complex aerodynamic models. It was believed that this type of flutter cannot occur in real structures due to its suppression by structural damping, but recent studies [3, 4] prove the possibility of its occurrence.

Aircraft gas-turbine engine designers were faced with compressor blade flutter in the middle of the 1950s while developing the second generation of jet engines. At the present day, a huge theoretical and practical experience has been accumulated. Basically, there are four methods for flutter prediction

[5, 6]. The most common method is based on analysis of large number of engine tests. Another method for flutter blades predictions is the frequency method. This method is based on the calculation of the eigenfrequencies of a coupled fluid–structure system. The positive imaginary part of the eigenfrequency is a criterion for flutter. However, the problem of calculating complex eigenvalues of asymmetric matrices requires large computational resources. Direct method is based on the direct time-domain numerical simulation of a coupled blade-flow. Finally, energy method is based on the calculation of the work done by the gas forces on the displacements of the elastic blade oscillating in a natural mode over one cycle of oscillation. This method provides acceptable results if the natural mode shapes in vacuum and in flow are similar, which is almost always true, except for hollow blades. If the work is positive and greater than the work of damping forces, then flutter occurs.

2. Energy method

We assume that the influence of the flow on natural oscillations of structure (blade or panel) is negligible. Therefore, the airflow can result only in small additional damping (for stability case) or additional energy inflow (for flutter case) without change of natural modes and frequencies. The energy equation of the structure:

$$\mathrm{d}E(t)/\mathrm{d}t = N(t) \tag{1}$$

where $E(t)$ is the total energy of the plate and $N(t)$ is the power of pressure forces. Then the change in energy over the oscillation period is defined as follows:

$$U = \Delta E = \int_0^T N\mathrm{d}t = \int_0^T\int_S p(x,y,z,t)\boldsymbol{n}(x,y,z,t)\cdot\mathbf{v}(x,z,t)\mathrm{d}s\,\mathrm{d}t, \tag{2}$$

where T is the oscillation period, S is the surface of the structure, $\boldsymbol{n}$ is the normal to the structure surface, and $\mathbf{v}$ is the velocity of the structure points.

Pressure work U Eq. (2) at the oscillation cycle is calculated as follows. The oscillations of the structure are set in the form of displacement of the corresponding domain surface (accompanied by the deformation of the computational grid) according to the eigenmodes in the vacuum. The oscillation of the structure leads to the perturbation of the gas pressure. If some time after the start of the oscillations, the response of the flow to the harmonic motion of the structure becomes harmonic, then the calculation is stopped and work U, done by the gas pressure at the last oscillation period, is calculated. The criterion of a flutter is the positivity of this work. Natural modes and frequencies of the structure in the vacuum are calculated by standard methods.

Aerodynamic calculations were conducted using the control volume method in Ansys CFX. Calculation of Eq. (2), which is based on the calculation results, was performed using an in-house program [7].

3. Single mode panel flutter

The stability of a thin elastic plate, exposed by one side to a homogeneous supersonic flow of perfect inviscid gas is investigated (Figure 1). We consider plates of rectangle and parallelogram shapes simply supported along all edges. Plates are investigated at various values of length. The influence of the skew angle for parallelogram plates was also considered.

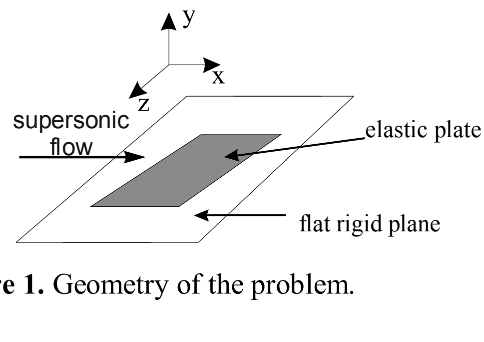

Figure 1. Geometry of the problem.

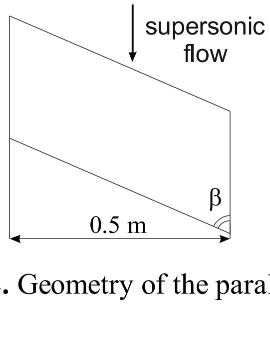

Figure 2. Geometry of the parallelogram panel.

3.1. Natural mode shapes and frequencies

We consider plates with thickness h = 0.001 m. The plate is made of steel with Young's modulus of $2{\cdot}10^{11}$Pa, Poisson's ratio of 0.3 and density of 7800 kg/m^3.

For a rectangular plate simply supported at all edges, natural mode shapes are as follows:

$$W(x,z) = A\sin(n\pi X^{-1}x)\sin(m\pi Z^{-1}z)\,, \quad (3)$$

where A is the normalised amplitude of the oscillations; n and m are the number of half-waves in the direction of flow and across it X and Z are the length and width of the plate. Natural mode frequency corresponding to this mode shapes is given by formula:

$$\omega = (D\rho^{-1}h^{-1})^{1/2}((n\pi X^{-1})^2 + (m\pi Z^{-1})^2) \quad (4)$$

The natural mode shapes of frequencies the parallelogram plates are calculated in Abaqus by the finite element method. The geometry of the plates varies so that the area remains unchanged (figure 2).

Using in-house software [7], Lagrange interpolation polynomials are constructed for mode shapes. Using these polynomials, the calculated oscillation modes are transferred to Ansys CFX.

3.2. Aerodynamic calculation

A model of gas flow over the plate is considered. The motion of the plate in the flow is forcefully predetermined in eigenmode [8], and the unsteady plate flow at its given oscillations is calculated.

Width (across the flow) and height of the domain are chosen so that the disturbances of the flow after reflection from the walls do not get on the plate, with the result that the flow around the plate corresponds to an unbounded flow.

Inside the domain, the Navier-Stokes equations are solved by the control volume method. The speed, pressure and temperature of the gas are set at the inlet; the values correspond to the standard atmosphere at sea level. The boundary conditions at the outlet are not set. On the remaining surface of the computational domain (including the plate), the slip condition is given: the tangential stress and the velocity normal to the surface are zero. The initial condition is an undisturbed homogeneous flow.

3.3. Results

We have computed single mode flutter boundaries in the first two modes rectangle and parallelogram panels with dimensionless panel lengths (L_x) from 0 to 350 (the length related to thickness). Panel width across the flow is 500. Parallelogram panels with various angles are considered. Investigation has been conducted at Mach numbers (M) from 1.05 to 1.7. Modes (1,1) and (2,1) were investigated for each plate (n = 1, m = 1 and n = 2, m = 1, respectively).

Figure 3a shows the comparison of single-mode boundaries in the mode (1,1) for parallelogram panel with β = 80°, 70° and 66° (dashed, dash-and-dot and dotted curves) and rectangular panel (β = 90° solid curve). Figure 3b shows single mode flutter boundaries in the mode (2,1) for rectangular panels.

The following results for rectangle panels can be seen:

- single mode flutter in mode (1,1) occurs for a certain range of Mach number at $76<L_x<244$
- for mode (2,1), flutter appears for a certain range of M at $L_x>106$.

For plates in the shape of parallelogram, the following is observed:

- for mode (1,1), flutter occurs for a range of M at $76<L_x<220$ (for skew angles β = 80°), $98<L_x<162$ (β = 70°) . When β is further decreased, the size of the single mode flutter region decreases and tends to the point and disappeared completely at β < 66°. So, for β < 66° the panel is fully stable with respect to the first-mode flutter
- for the second mode, flutter boundaries changed too when the skew angle is varied

IOP Conf. Series: Journal of Physics: Conf. Series **1129** (2018) 012001 doi:10.1088/1742-6596/1129/1/012001

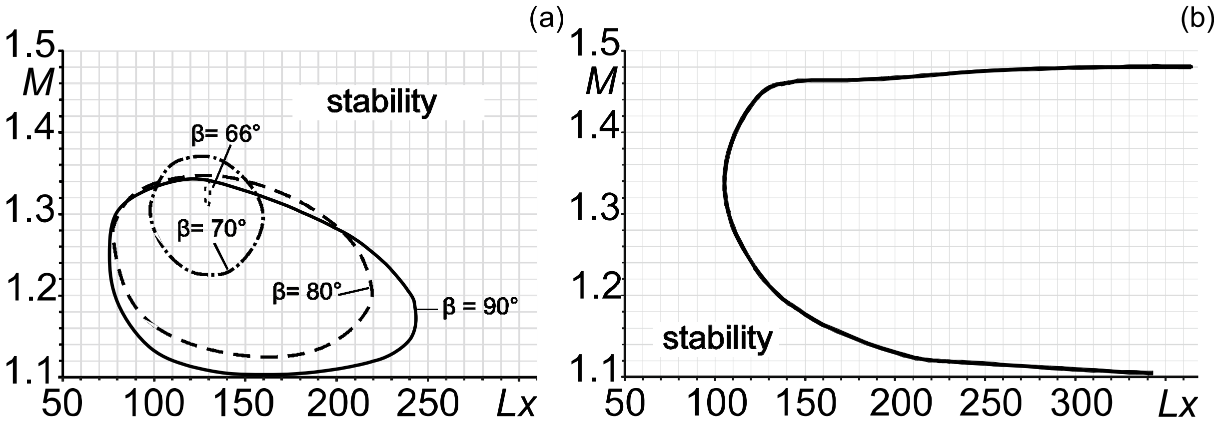

Figure 3. Single mode flutter boundaries.
(a) Parallelogram panel, mode (1,1) (b) rectangle panel mode (2,1).

4. Blade flutter

The stability of the first-stage shrouded blades of a low-pressure compressor is investigated. The influence of various design parameters (radial and axial clearance, closure and opening of the inlet guide vane, radial flow irregularity, inter-blade tension in the mid-span shroud) on flutter boundary is analyzed. The gas flow in blade channel is turbulent. Gas is perfect and viscous.

4.1. Aerodynamic calculation

Finite-volume model of the flow consists of three consecutive blade passages of one stage (figure 4). For unsteady fluid flow analysis, initial and boundary conditions (figure 4) are extracted from the steady-state flow calculated for the full compressor (where all stages are modelled), verified by full-scale compressor tests.

Mesh displacement in the form travelling wave corresponding to the wheel natural mode with a specified number of nodal diameters is applied to each blade surface [9]. For modelling a forward (or backward) traveling wave, a phase lag $\omega t-\varphi$ and lead $\omega t+\varphi$ with respect to the middle blade are specified for neighbouring blades, where the phase shift $\varphi=2\pi m/N$ corresponds to the number of nodal diameters m (N is the number of blades).

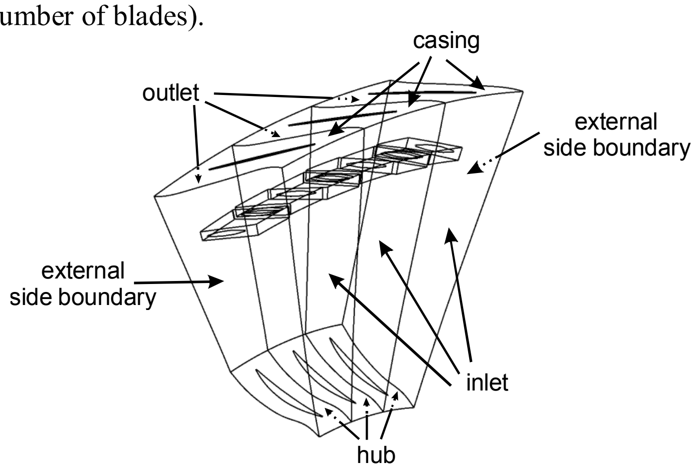

Figure 4. Model of three consecutive blade passages.

4.2. Results

The work done by pressure is calculated for the second and third natural modes. Each mode was analyzed in a full range of possible numbers of nodal diameters. A series of computational models, representing the change of one of the design parameters, was considered. The following configurations were studied:

1. Increased radial clearance by 0.5 mm
2. Increased radial clearance by 0.5 mm and shut by 1.5° inlet guide vane
3. Increased radial clearance by 0.5 mm and opened by 2° inlet guide vane
4. Increased radial clearance by 1 mm
5. Specified radial non-uniformity of the flow at the inlet

The calculations were carried out on a flow regime in which a flutter was observed during engine tests. The amplitude was normalized such that the maximum blade displacement was 0.001 m. The inter-blade tension at the mid-span shroud in the main series of calculations was 0.54 mm.

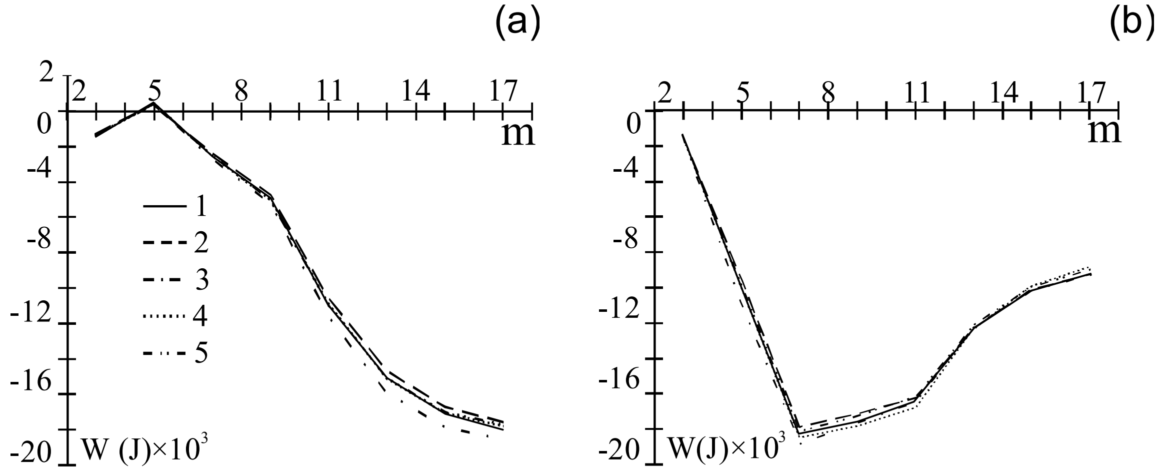

Figure 5. Work done by unsteady pressure vs nodal diameter. Mode 2 (a), 3 (b).

For the baseline mode, as well as for cases 1-5, calculation results predict the occurrence of flutter for the second mode at m=5 (figure 5). It is seen that the change of the design parameters considered in cases 1-5, does not result in significant change of the work done by pressure over the oscillation cycle.

An additional series of calculations was carried out to determine the influence of the inter-blade tension in the mid-span shrouds on flutter boundary (figure 6). The value of the work at each nodal diameter differs greatly for different values of the inter-blade tension. Results for inter-blade tension equal to 0.27 mm and 0 mm at almost all nodal diameters are close to each other because at these values of the inter-blade tension natural mode shape and frequencies are close. Thus, the influence of the inter-blade tension in the mid-span shrouds on flutter prediction is significant.

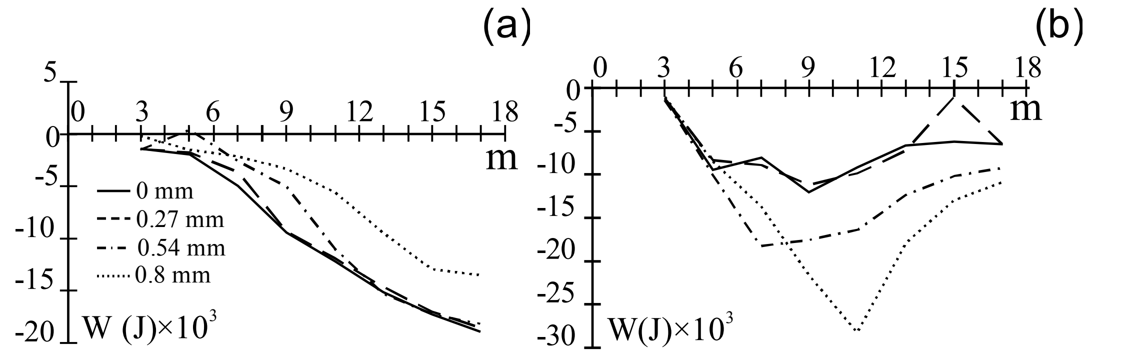

Figure 6. Work done by unsteady pressure vs nodal diameter. Mode 2 (a), 3 (b).
Curve 1 – 4 blade model with different inter-blade tension.

5. Conclusions

By using the energy method, the stability of panels with rectangle and parallelogram shapes in a low supersonic gas flow, where a single-mode flutter occurrence is possible, and the influence of various design parameters on blade flutter prediction have been studied.

Results for mode (1,1) show that when skew angle of a parallelogram panel decreases, single-mode flutter boundary contacts to a point, and starting from a certain angle, region of single-mode flutter disappears completely. Flutter boundaries for mode (2,1) change when the skew angle is varied. The results obtained show that making the aircraft skin panels in the shape of a parallelogram can be an effective method of single-mode flutter suppression at transonic and low supersonic flight speeds.

It is shown that the results of blade flutter calculations differ insignificantly when the following parameters are changed: radial clearance, axial clearance, angle of closing / opening of the guide vane, radial flow non-homogeneity. Thus, these parameters almost do not affect the flutter boundary.

At the same time, a significant effect of the inter-blade tension in the mid-span shroud on the flutter prediction is shown, which is caused by its influence on the change of the blade mode shapes.

References

[1] Bisplinghoff R, Ashley H and Halfman H 1955 *Aeroelasticity* (Cambridge, Massachusetts: Addison-Wesley Publishing Company)

[2] Dowell E 1974 *Aeroelasticity of Plates and Shells* (Leyden: Noordhoff International Publishing)

[3] Vedeneev V 2005 Flutter of a wide strip plate in a supersonic gas flow *Fluid Dyn.* **5** 805–817

[4] Vedeneev V, Guvernyuk S, Zubkov A and Kolotnikov M 2010 Experimental observation of single mode panel flutter in supersonic gas flow *J. Fluids Struct.* **26** 764–779

[5] Marshall J and Imregun M 1996 Review of aeroelasticity methods with emphasis on turbomachinery applications *J. Fluids Struct.* **10** 237–267

[6] Shrinivasan A 1997 Flutter and resonant vibration characteristics of engine blades *J. Eng. Gas Turb. Power* **119** 742–775

[7] Vedeneev V, Kolotnikov M and Makarov P 2015 Experimental validation of numerical blade flutter prediction *J. Propul. Power* **31** 1281–91

[8] Abdukhakimov F and Vedeneev V 2017 Investigation of single-mode flutter of various shape plates at low supersonic speeds *TsAGI Sci. J.* **48** 97–110

[9] Vedeneev V, Kolotnikov M, Mossakovskii P, Kostyreva L, Abdukhakimov F, Makarov P, Pyhalov A and Dudaev M 2018 A comprehensive solution of the problems of ensuring the strength of gas turbine engine compressor at the design stage *IOP Conf. Ser.: Mater. Sci. Eng.* **302** 012079