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SINGLE MODE FLUTTER OF NON-RECTANGULAR FLAT PANELS AT LOW SUPERSONIC SPEEDS

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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. In this paper, we investigate a single-mode flutter of panels of different shapes; namely, trapezoidal and parallelogram plates are considered. The panel is modeled as simply supported elastic plate, the air is considered inviscid and perfect. To calculate flutter boundaries in the first two eigenmodes, we use the energy method. We show that flutter boundaries for trapezoidal plates vary slightly in comparison with rectangular plates. On the contrary, for parallelogram plates even at a small skew angle the aeroelastic stability increases significantly. 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.

NOMENCLATURE

A normalised amplitude of the oscillations
D bending stiffness
E total energy of the plate, Young's modulus
h plate thickness
L_x dimensionless plate length
M Mach number
n, m number of half-waves in the direction of flow and across it
$\mathbf{n}$ normal to the plate surface
p pressure acting on the plate surface
t time
U work done by pressure
$\mathbf{v}$ velocity of the plate points
w plate deflection
x, y, z spatial coordinates
X, Z length and width of the plate
W mode shape
α, β skew angle of trapezoidal and parallelogram panels
δ oscillation growth rate
ν Poisson's ratio
ρ the density of the panel material
ω circular eigenfrequency

INTRODUCTION

Panel flutter is a phenomenon of self-exciting vibrations of skin panels of flight vehicles moving at high speeds. Usually panel flutter does not lead to immediate destruction of the aircraft, but results in the accumulation of fatigue damage of panels and the decrease of their lifetime (Dowell [1]). At transonic and low supersonic speeds, panel flutter occurs in the form of single mode flutter, i.e. without interaction between panel eigenmodes (Vedeneev et al. [2] and Shishaeva et al. [3]), in contrast to coupled-mode flutter, which occurs at higher speeds.

Single mode flutter cannot be studied by employing aerodynamic piston theory, which is widely used in supersonic aeroelasticity, because this theory is not valid at low supersonic speeds. In this study, the energy method is used (Vedeneev et al [4]). In the case of the single-mode flutter, the gas flow effect on the plate oscillation type is small and leads only to aerodynamic damping, either positive or negative. The goal of this work is the investigation of the effect of shape of skins panels on single mode flutter boundaries.

PROBLEM FORMULATION AND METHOD OF SOLUTION

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

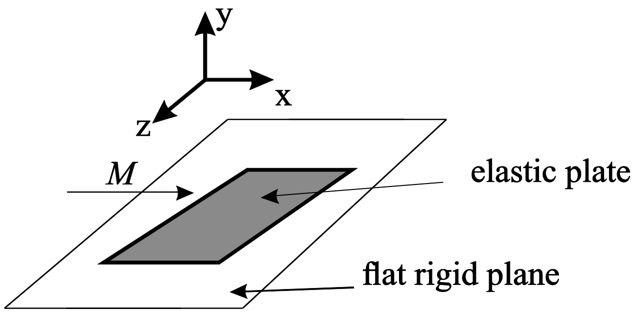

FIGURE 1: GEOMETRY OF THE PROBLEM.

Panel flutter problem consists in the stability analysis of equation

$$D\left(\frac{\partial^4 w}{\partial x^4}+2\frac{\partial^4 w}{\partial x^2 \partial z^2}+\frac{\partial^4 w}{\partial z^4}\right)+\rho h\frac{\partial^2 w}{\partial t^2}+p=0 \qquad (1)$$

Having multiplied both sides of Eq (1) by $\frac{\partial w}{\partial t}$ and having taken the double integral over the plate area, we obtain the energy equation of the plate:

$$\frac{dE(t)}{dt}=-\int_S p(x,y,z,t)\mathbf{n}(x,y,z,t)\cdot\mathbf{v}(x,z,t)ds \quad (2)$$

Then the change of the total energy over the oscillation period is calculated as follows:

$$\Delta E=U=-\int_0^T\int_S p\mathbf{n}\cdot\mathbf{v}ds\,dt \qquad (3)$$

Since we study the single-mode flutter, the eigenmodes and oscillation frequencies of the plate in the flow and in the vacuum coincide and are calculated by standard methods. Work done by pressure (Eq(3)) at the oscillation cycle is calculated as follows. We simulate the gas flow over the plate. The oscillations of the plate are specified in the form of displacement of its surface of the computational domain (accompanied by the deformation of the computational grid) according to the eigenmodes in the vacuum:

$$w(x,z,t)=W(x,z)\cdot sin(\omega t) \qquad (4)$$

The oscillation of the plate leads to the perturbation of the gas pressure. When the response of the flow to the harmonic motion of the plate becomes harmonic, the calculation is stopped and work U, done by the gas pressure at the last oscillation period, is calculated.
The sign of U is the flutter criterion. Indeed, the motion of a free plate in the gas flow in the linear approximation has the form:

$$w(x,z,t)=W(x,z)\cdot sin(\omega t)e^{\delta t} \qquad (5)$$

If the work $\boldsymbol{U}$ is positive, then the energy flow is directed from the gas to the plate, and the oscillations of the plate will be amplified. Otherwise, the energy flow will be directed from the plate to the gas; in this case, the oscillations of the plate will decay. The work done over the growing or damped oscillations Eq (5) for small values of δ (which is the case for single-mode flutter) differs from the work done over oscillations with a constant amplitude Eq (4) by a second order infinitesimal term. which is neglected.
This method is verified on the problem of flutter of rectangular plate, where the results of flutter study in the fully coupled formulation are known (Shitov&Vedeneev [5]), and then it is applied to the calculation of plates of non-rectangular shapes.

AERODYNAMIC CALCULATION

Simulation of the oscillating plate flow were conducted using the control volumes method in Ansys CFX. The calculation of the work Eq (3) based on the simulation results is performed using in-house program [4].
The size of the computational domain across the flow and in height is 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. 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 walls of the computational area (including the plate), the free-slip condition is specified: the tangential stress and the normal velocity to the surface are zero. With this formulation, no boundary layer is formed on the plate surface and the effect of viscosity does not appear. The initial condition is an unperturbed homogeneous flow in the entire region.

NATURAL MODE SHAPES AND FREQUENCIES OF PLATES

We consider plates of thickness h = 0.001 m. The properties of the plate material correspond to steel:

$$E=2\cdot 10^{11}\text{ Pa},\ \ \nu=0.3,\ \ \rho=7800\ \frac{kg}{m^3}$$

For a rectangular plate simply supported at all edges, eigenmodes are as follows:

$$W(x,z)=Asin\left(\frac{n\pi x}{X}\right)sin\left(\frac{m\pi z}{Z}\right)$$

Natural frequency corresponding to this mode is given by expression:

$$\omega=\sqrt{\frac{D}{\rho h}}\left(\left(\frac{n\pi}{X}\right)^2+\left(\frac{m\pi}{Z}\right)^2\right)$$

Natural frequencies and mode shapes of non- rectangular plates are calculated in Abaqus by the finite element method. The geometry of the plates varies so that the area remains unchanged (Fig.2). Using in-house software [4], Lagrange interpolation polynomials are constructed for each mode shapes. Using these polynomials, the calculated oscillation modes are transferred to Ansys CFX.

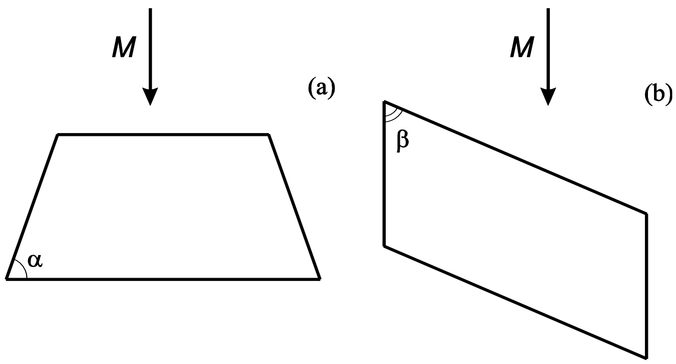

FIGURE 2: PLATE GEOMETRY A) TRAPEZOIDAL, B) PARALLELOGRAM

VERIFICATION

To verify the energy method for panel flutter analysis, flutter boundaries of rectangular panels are calculated and compared with the fully coupled aeroelastic solution (Shitov&Vedeneev [5]). Single mode flutter boundaries in the first mode are shown in $L_x - M$ plane in Fig.3.

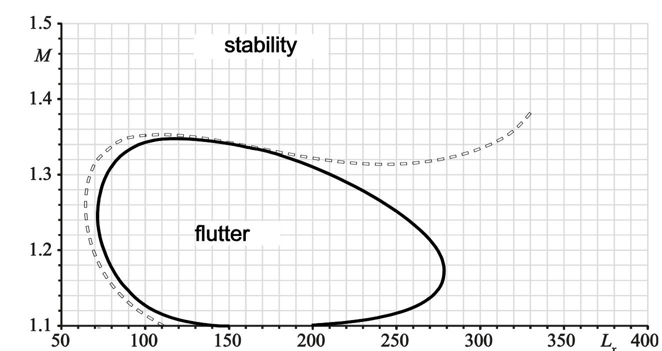

FIGURE 3: SINGLE MODE FLUTTER BOUNDARIES OF RECTANGULAR PANELS

Comparison of the results obtained in this paper (solid curve) and in [5] (dashed curve) shows a satisfactory agreement for $L_x < 200$. At $L_x > 200$ the results of the calculation [5] are affected by the coupled-mode flutter region: the assumption that the influence of the flow on the plate is insignificant becomes incorrect in this region, and the plate mode shape in the flow changes in comparison with vacuum. Due to this reason, there is a discrepancy of the coupled aeroelasticity problem solutions (Shitov&Vedeneev [5]) and the method used here.

RESULTS

We have computed single mode flutter boundaries in the first two modes for trapezoidal and parallelogram panels with panel lengths from 0 to 350 (non-dimensionalized by panel thickness). Panel width across the flow is 500. Panels with various angles are considered. Investigation has been conducted at Mach numbers from 1.05 to 1.7. Figure 4a shows the comparison of single-mode boundaries in the 1st mode for trapezoidal panel with α = 70° and α = 50° (dashed and dotted curves) and rectangular panel (solid curve). Figure 4b shows same boundaries in the 2nd mode for trapezoidal panel with α = 50° (dotted curves) and rectangular panels (solid curve).

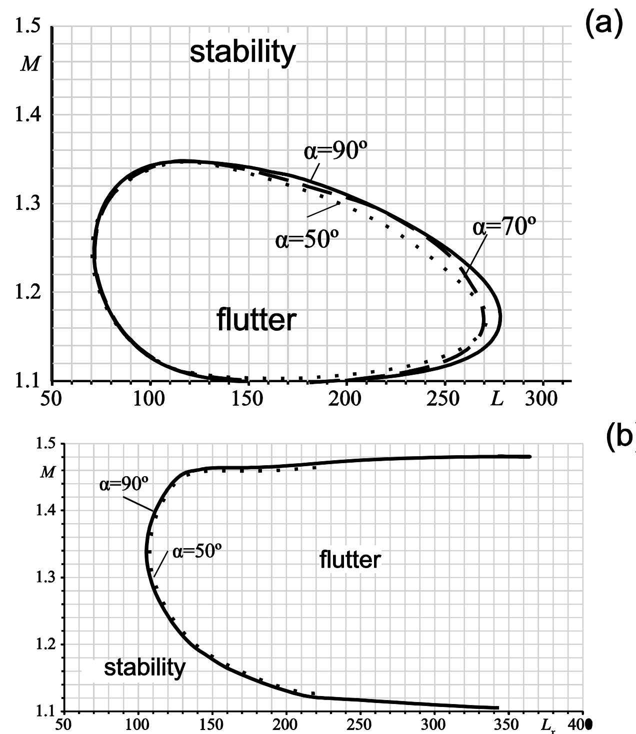

FIGURE 4: SINGLE MODE FLUTTER BOUNDARIES OF TRAPEZOIDAL PANELS A) 1ST MODE, B) 2ND MODE,

The following results for trapezoidal panels can be seen:

- single mode flutter in the first mode occurs for a certain range of Mach number at $73 < L_x < 268$ (for skew angles α = 70°) and at $73 < L_x < 270$ (α = 50°).
- for the second mode, flutter appears for a certain range of M at $L_x > 70$ (α = 50°) .

It is seen that flutter boundaries for trapezoidal panels almost do not change when the skew angle is varied.

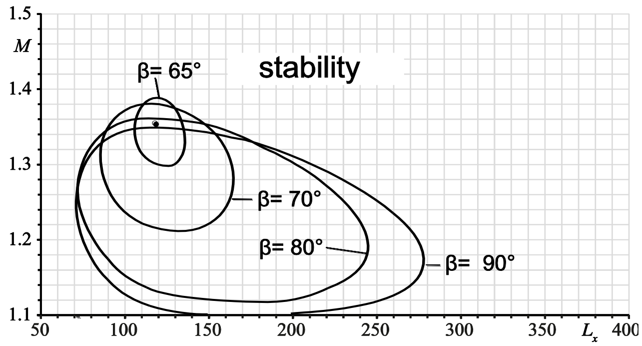

FIGURE 5: SINGLE MODE FLUTTER BOUNDARIES OF PARALLELOGRAM PANELS

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

- for the first mode, flutter occurs for a range of M at $76 < L_x < 245$ (for skew angles β = 80°), $86 < L_x < 166$ (β = 70°) and $106 < L_x < 167$ (β = 65°). When β is further decreased, the size of the single mode flutter region decreases and tends to the point $\mathrm{L_x} \approx 118, \mathrm{M} \approx 1.35$, and disappeared completely at β = 64°.
- for β < 64° the panel is fully stable with respect to the first-mode flutter

CONCLUSION

By using the energy method, we have studied the stability of panels with trapezoidal and parallelogram shapes in a low supersonic gas flow, where a single-mode flutter occurrence is possible. The comparison of calculation results for plates in the shape of a trapezoid and a parallelogram with rectangular plates shows that the flutter boundaries of the trapezoidal plates are close to those of rectangular plates.

On the contrary, 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.

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.

ACKNOWLEDGMENTS

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