Cascade of bifurcations in nonlinear transonic panel flutter oscillations

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Summary. We investigate nonlinear self-exciting oscillations of elastic plate in transonic flow at unsteady flow conditions: the flow speed is variable in time with different rates. By observing unsteady plate behaviour, we detect bifurcations of limit cycle oscillations. In addition to previously known limit cycle types, new bifurcations of limit cycles are discovered, and their physical nature is revealed. When increasing acceleration of the flow, some of the limit cycles disappear, because they do not have enough time to develop. However, flutter is not fully suppressed even for very high accelerations, though the most destructive higher-mode oscillations are missed.

Introduction

Aeroelastic instability of skin panels, known as panel flutter, has been intensively studied over decades [1, 2]. At high supersonic speeds the coupled-mode panel flutter occurs, while at low supersonic speeds the single-mode flutter is dominant [3, 4]. Recent nonlinear study [5] has shown that at small supersonic flight speeds, different limit cycles can coexist at the same flight conditions, which is caused by linear growth mechanism and nonlinear interaction between growing eigenmodes. Some of the limit cycles include internal resonance between natural modes [6]. Switches of panel oscillations from one limit cycles to another is accompanied by bifurcations of the aeroelastic dynamic system. In the present paper we study such bifurcations by varying the flow speed at different rates, and watching the unsteady panel response. This approach gives an explicit and convenient way to note the bifurcations in the limit cycles and reveals additional bifurcations not noticed before.

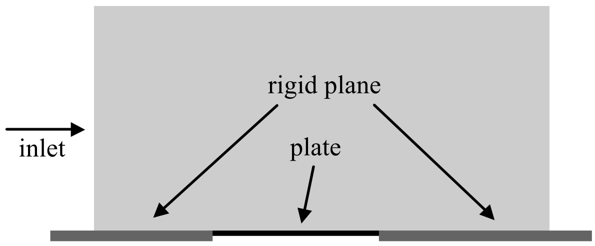

Figure 1: Simulation domain.

Formulation of the problem

Elastic plate is mounted into a rigid plane (Fig. 1) with the leading and trailing edges clamped. Inviscid gas flows over one side of the plate with variable inlet Mach number $M(t)$. At the other side of the plate, a pressure equal to the undisturbed flow pressure is assigned, such that the undisturbed pressure difference along the plate is zero. Linear increase of M in time from $M_1 = 0.7$ to $M_2 = 1.7$ with various increase rates is considered:

$$M(t) = M_1 + (M_2 - M_1)(t/T),$$

where the time interval was $T = 10$, 7.5, 5, 2.5, 1, 0.5, 0.1, 0.05 s. The plate-flow interaction is calculated using two coupled codes, Abaqus for simulating the plate, and FlowVision for simulating the gas flow [5]. During each run a slight disturbing harmonic force is applied to the plate in order to enforce each bifurcation of the plate oscillations.

Results

For sufficiently low accelerations, $T \geq 5$ s, the following bifurcations are seen (Fig. 2a). First, at $M = 0.78$ the plate becomes unstable, and static divergence appears, which signifies pitchfork bifurcation. At transonic speed, $M = 1$, Hopf bifurcation occurs, resulting in the first-mode flutter of the plate. At slightly higher Mach number $M = 1.09$ transition from non-resonant to 1:2 resonant limit cycle occurs, which is expressed in the non-symmetry of the oscillations (Fig. 2), the appearance of the second mode in the oscillation shape and additional doubled frequency present in the spectrum. At $M = 1.41$ higher modes appear, and the oscillations become non-periodic. Finally, at $M = 1.7$ transition to stability occurs. At higher Mach numbers (not considered here) coupled mode flutter occurs.
The variety of limit cycles observed at transonic conditions is in agreement with [5], where flutter at constant flow speed was studied. Analysis of the problem with variable flow speed yields the detection of two minor bifurcations at $M = 1.07$ and $M = 1.2$, which are slightly visible in Fig. 2a by non-smoothness of $A(M)$ slope, and much better seen in the phase portraits. For each bifurcation, the change in the plate spectrum, phase portrait, and spatial oscillation mode are analyzed. For faster increase of M, some of the limit cycles are not formed, since their formation periods are too large. For example, for $T = 2.5$ s (Fig. 2b) no non-periodic oscillations are observed. However, even for extremely fast increase of

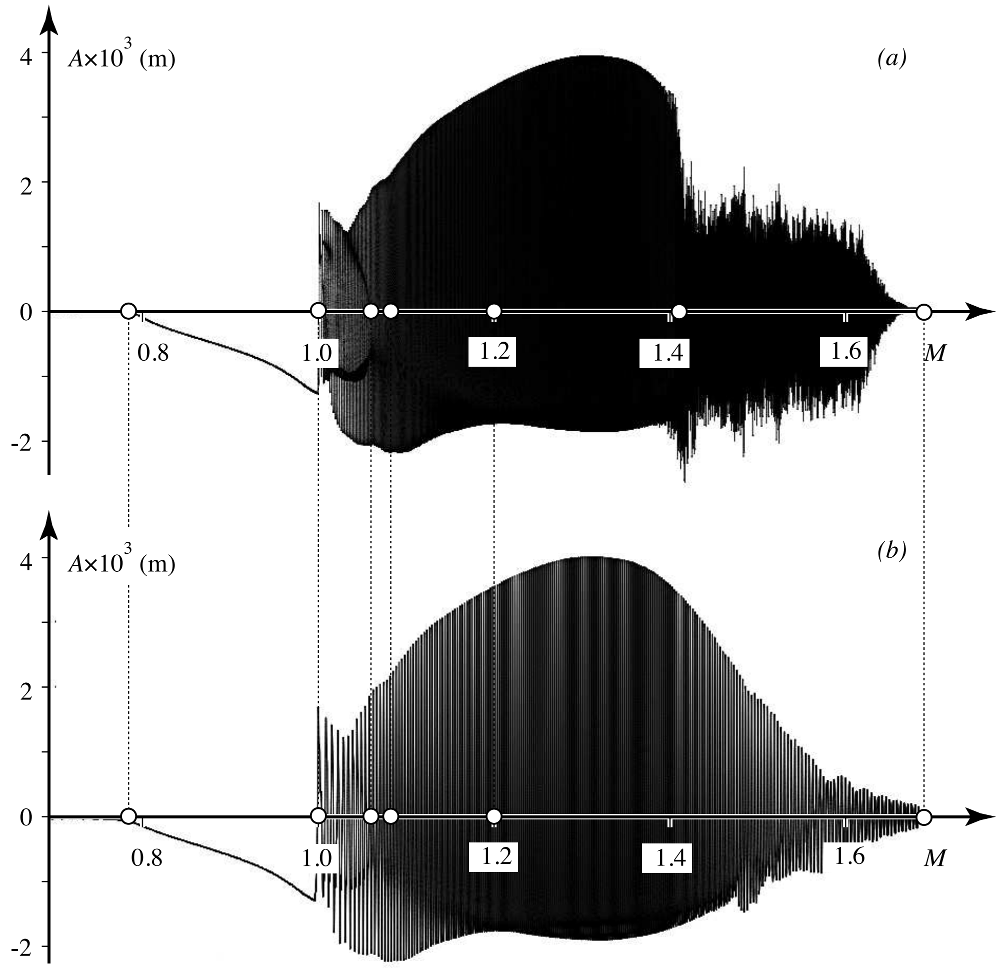

Figure 2: Vertical deflection of a plate point vs M, circles represent bifurcations of the limit cycle. Acceleration corresponding to $T = 10$ s (a), 2.5 s (b).

M, $T = 0.05$ s (for the air at normal conditions it corresponds to the acceleration of 66g), first mode flutter oscillations are still formed, though more dangerous high-frequency oscillations are missed.
Thus the sufficiently high acceleration of a flight vehicle moving at transonic flow conditions is favourable not only because of shorter time passed in transonic flutter regime, but also because the most destructive limit cycle oscillations (involving higher modes) can be avoided.

Conclusions

In this paper, we have arranged bifurcation of limit cycles observed in nonlinear panel flutter oscillations at transonic and low supersonic speeds. Some of limit cycles are due to internal resonances between plate eigenmodes, others are due to travelling-wave reflections. For low accelerations, or constant speed, the most dangerous is the non-periodic high-frequency vibrations. When increasing the flow acceleration, the most destructive higher-mode limit cycles disappear, because the time passed in the region of their existence is less than the time needed for their development. However, first-mode limit cycle is present even at extremely high acceleration, so that it cannot be fully avoided.
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