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Panel Flutter Investigation including Thermal Effects through the FEM

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Abstract. Thermal effects in aeroelastic stability are of the main concern of super and hypersonic vehicles, since the aerodynamic heating causes, with the rise of temperature, the degradation of elastic properties of the material and, in addition, compressive stresses due to thermal expansion, which can make flutter more critical. In recent decades authors have developed non-linear methods in order to verify this behaviour. This paper aims to verify if the use of the FEM in a two steps analysis employing the Nastran software with a non-linear heat transfer analysis and subsequent eigenvalue flutter analysis can produce results agreeable with the literature. It is used in the linear third-order Piston Theory with Van Dyke's correction for aerodynamic modelling and the Mindlin-Reissner plate theory for structural modelling. The PK method is used to solve the aeroelastic eigenvalue problem in a range of flow conditions in order to determine the instability boundary. The results are obtained from a metallic simple-supported square panel.

Keywords: panel flutter, flutter, aerothermoelasticity,aeroelasticity

1 Introduction

The panel flutter is a self-excited instability generated by the passage of air at a critical velocity through one side of the skin plate of missiles, rockets, and supersonic and hypersonic vehicles. The air at high speeds can cause aerodynamic heating, generating thermal stresses, reducing the critical dynamic pressure and causing panel buckling.

This instability began to be studied after accidents involving V-2 Bombs and has been extensively studied in the last century. Several researchers such as FUNG [1],DOWEL [2, 3] and BISMARCK-NASR [4] studied and modelled the phenomenon initially to determine the stability boundaries and later the post-flutter behaviour.

The effects of high-speed aerodynamic heating were initially studied on isotropic materials using Linear Piston Theory and Galerkin Method or the Finite Element Method (FEM) to discretize the differential equations (CHENG and MEI [5], SCHAEFFER and HEARD [6], YANG and HAN [7] and XUE D. Y. MEI [8]). Thermal effects on laminates were studied using FEM and Galerkin to study limit cycle oscillation and nonlinear behaviour due to nonlinear aerodynamics and the structural model (DAI and SUN [9], ZAFER and ZAHIT [10], GANAPATHI and TOURATIER [11],LIAW [12]).

This work presents the Thermal effects of aeroelastic stability in supersonic and hypersonic flows. The rise of the temperature modifies the structural model, with the degradation of elastic properties of the material and the compressive stresses generated due to thermal expansion. Consequently, the critical pressure is reduced. The Nastran software is used to model the structural, thermal and aeroelastic. The PK method solves the aeroelastic eigenvalue problem and determine the instability boundary. A simple-supported square panel with metallic material are studied. The modes and the comparison with the literature are shown.

2 Methodology

The problem stated, illustrated in the Figure 1, is composed of a single metallic square panel of thickness t, of length a, subjected to supersonic flow at given Mach number M and dynamic pressure $\bar{q}$. The plate is subjected to thermal heating of magnitude ΔT.

The model is discretized through the FEM in a 20x20 CQUAD4 element grid. All the elements free-edge nodes are constrained in its displacements DOF (i.e. simply-supported plate). Nastran FEM solver will be used with solutions 153 (Steady-State Heat Transfer) and 145 (Flutter Analysis).

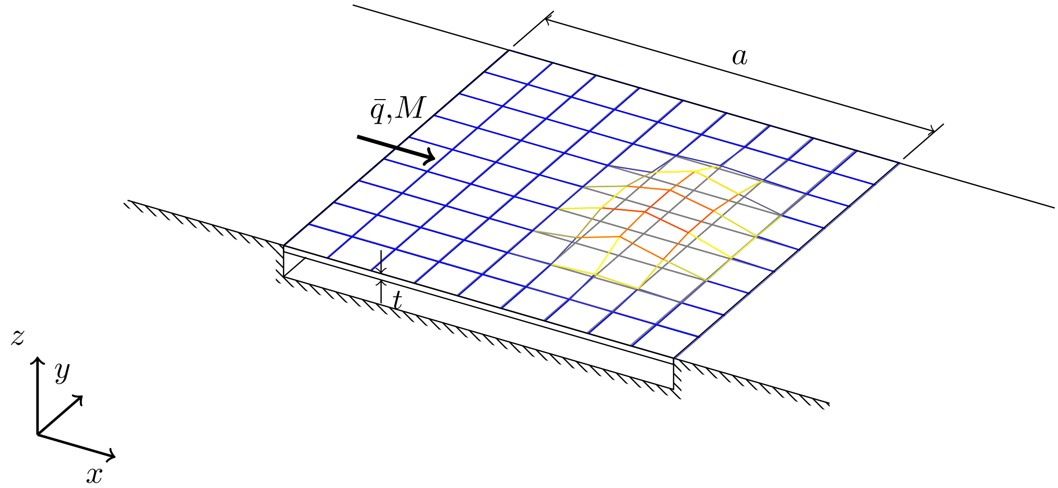

Figure 1. Panel flutter model of a square plate.

2.1 Structural model

The Nastran's shell finite element uses Mindlin-Reissner theory. The plate theory include transverse shear deformation and the displacement are expanded as linear combination of the thickness of the laminate coordinate reducing the 3D problem to a 2D problem. The first-order shear deformation theory is known more commonly as "the Mindlin-Reissner plate theory".

2.2 Aerodynamic model

The aerodynamic model used is a linear thrid order Piston Theory with Van Dyke's correction. This theory defines a relation between pressure and motion as stated in Eq. 1, where U_∞ is the undisturbed flow velocity, a_∞ is the undisturbed speed of sound, and γ_{air} is the air specific heat ratio.

$$p = p_\infty \left[1 + \frac{\gamma_{air} - 1}{2a_\infty}\left(\frac{\partial w}{\partial t} + U_\infty \frac{\partial w}{\partial x}\right)\right]^{\frac{2\gamma_{air}}{\gamma_{air}-1}} \quad (1)$$

This equation can be expanded in a power series as shown in Eq. 2 where λ is the dynamic pressure. This equation is commonly truncated in it's first, second or third terms.

$$\begin{aligned} p - p_\infty = \frac{2\lambda}{\sqrt{M^2-1}} \Bigg[&\left(\frac{1}{U_\infty}\frac{\partial w}{\partial t} + U_\infty \frac{\partial w}{\partial x}\right) \\ &+ \frac{\gamma_{air}+1}{4} M \left(\frac{1}{U_\infty}\frac{\partial w}{\partial t} + U_\infty \frac{\partial w}{\partial x}\right)^2 \\ &+ \frac{\gamma_{air}+1}{12} M^2 \left(\frac{1}{U_\infty}\frac{\partial w}{\partial t} + U_\infty \frac{\partial w}{\partial x}\right)^3 + \cdots \Bigg] \end{aligned} \quad (2)$$

2.3 Thermal modeling

The increase in temperature causes an increase in thermal stresses and the consequent buckling of the plate. The dynamic pressure also reduces as the temperature varies. In order to determine the effects of the thermal expansion in the flutter speed the problem is divided in two sections. First, a non-linear steady-state heat transfer analysis is performed with all the desired temperature steps. This enables the creation of stiffness matrices that account for the compressive stresses for each temperature step. Secondly, a flutter analysis is performed for each temperature step utilizing a restart feature, that it's capable of using the indicated stiffness matrix in the analysis. Finally, the results in the .f06 file are parsed and processed trough python scripts.

3 Results

The Figures 2, 3,and 4 shows the Vf-Vg plots for each variation of the temperature ratio to buckling. It can be observed the reduction of flow speed that the mode coalescence occurs, indication the transition to the instability.

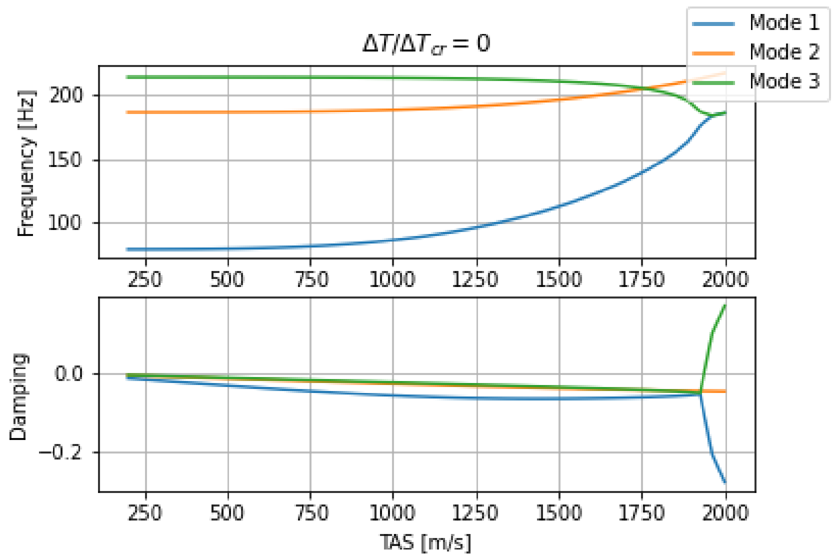

Figure 2. The Vf-Vg results for $\Delta T/\Delta T_{cr} = 0$.

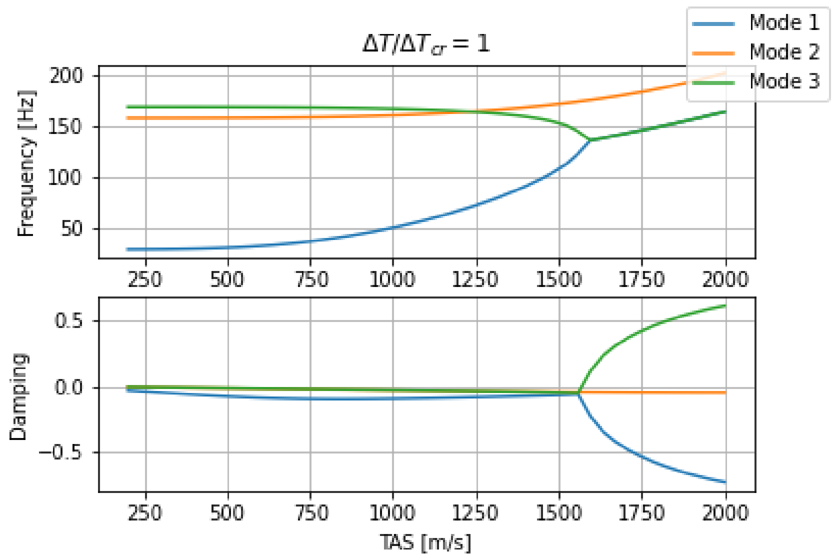

Figure 3. The Vf-Vg results for $\Delta T/\Delta T_{cr} = 1$.

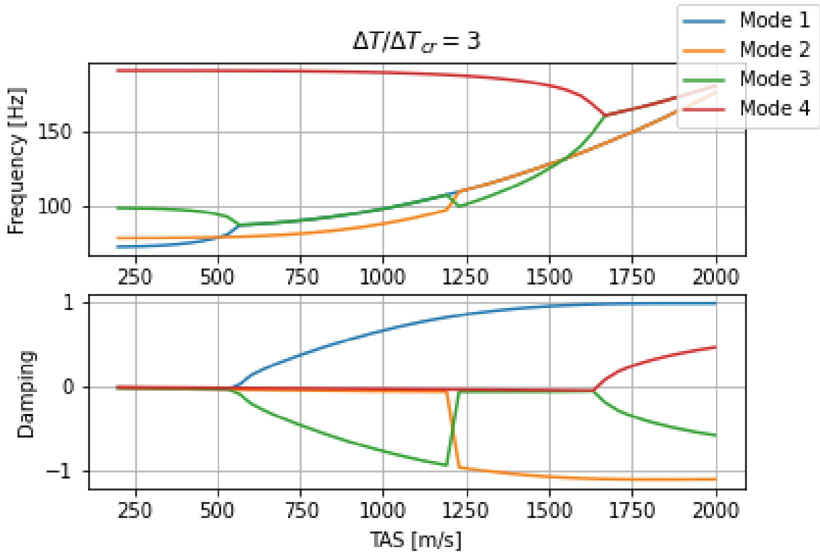

Figure 4. The Vf-Vg results for $\Delta T/\Delta T_{cr} = 3$.

The Figure 5 shows the variation of λ with the temperature up to the buckling temperature of the plate. The results indicate a linear decreasing effect with the raise of temperature, as expected, however it have a steeper derivative than the presented in the literature.

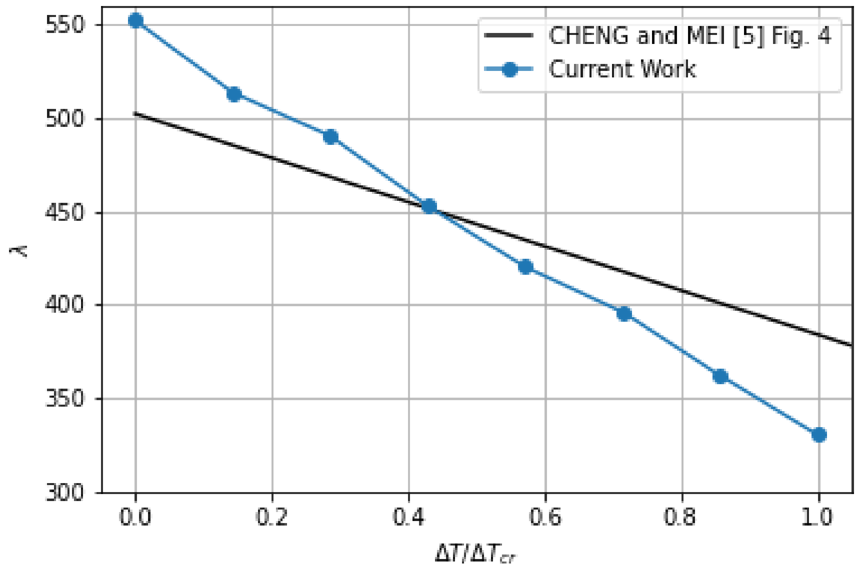

Figure 5. The stability boundary varying with the temperature up to buckling temperature compared with the literature.

The Figure 6 indicated a significant drop in the flutter non-dimensional aerodynamic pressure after it reaches the buckling critical temperature. This effect is accounted to the non-linear analysis made by Nastran as it considers it a post-thermal-buckling analysis. Therefore, the stabilizing effect of the aerodynamic load at low speeds cannot be computed through Nastran. This is also the possible reason on why the decrease of the non-dimensional aerodynamic pressure is slightly steeper than the reference.

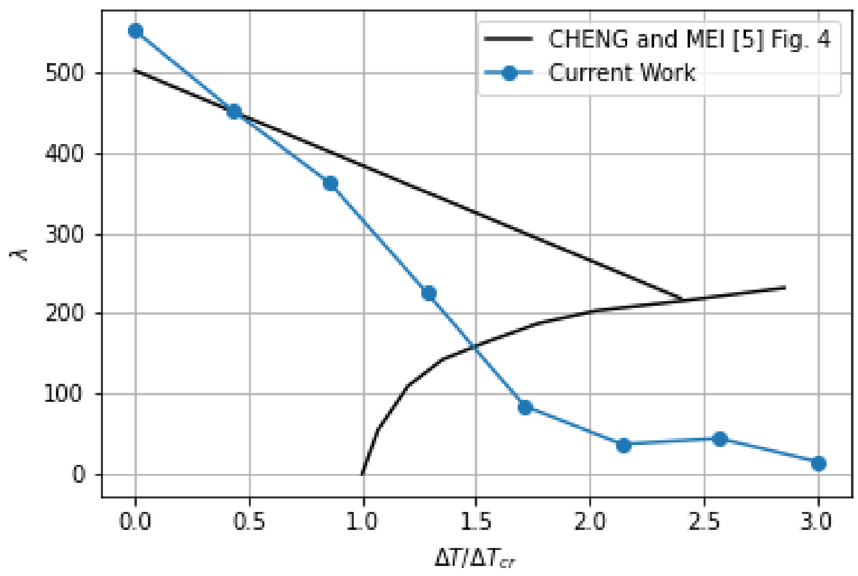

Figure 6. The stability boundary varying with the temperature compared with the literature.

4 Conclusions

In the present work a analysis methodology was developed for determining the thermo-aeroelastic stability boundaries. The developed methodology is limited to the critical thermal-buckling temperature, as Nastran does not takes in account the stabilizing effect of the aerodynamic load on the place. However, the results agree with the literature until the critical thermo-buckling temperature. Future works may use this capability to analyze laminated composite materials.

Acknowledgements. This section should be positioned immediately after the Conclusion section. Type Acknowledgements in boldface, 10 pt Times New Roman type from left margin, leaving 20 pt line spacing before and 12pt after.

Authorship statement. This section is mandatory and should be positioned immediately before the References section. The text should be exactly as follows: The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

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