QUAD LAMINATES AEROELASTIC INSTABILITY

Helio de Assis Pegado[1]

[1] *Dept. of Mechanical Engineering, Universidade Federal de Minas Gerais*
Av. Antônio Carlos, 6627, Pampulha, 31270-901, - Belo Horizonte/Minas Gerais, Brazil
helio@demec.ufmg.br

Abstract. The flutter in panels of rockets, missiles, and vehicles was identified when technological advances allowed these vehicles to reach supersonic and hypersonic speeds. The phenomenon was first noticed and recognized during World War II, when the German V2 rockets were being developed. The initial studies used the Ritz and Galerkin approach based on a linear aerodynamic and structural model intended to determine the critical dynamic pressure. Researchers started using nonlinear structural models with a nonlinear aerodynamic model and obtaining the limits cycle oscillation (LCO) due to computer advances and the growing use of matrix techniques, such as finite elements. In the last ten years of the previous century, structural components and aircraft wings began to utilize composite materials like carbon and glass fiber on a large scale. Thus, the researchers began to verify the impact of using these materials on structures subject to this instability. This paper investigates the aeroelastic stability of laminate panels in supersonic flow. It is optimized to obtain the best fiber direction and number of layers to increase the critical dynamic pressure. The researchers discovered that quadriaxial laminates with predetermined directions have several advantages over others. In order to reduce flutter, the impact of employing quad laminate sets will be examined and contrasted with that of alternative configurations. The analysis is performed using a specially customized program. Finally, the results are compared with the literature, and the differences are analyzed.

Keywords: panel flutter, orthotropic panel, quad laminates, aeroelastic instability

1 Introduction

The aeroelastic instability known as panel flutter was widely studied and mathematically modelled, and the researchers understood how to avoid it in most situations. However, introducing new manufacturing methods and increasing the use of composites created new challenges, and new research fields moved the scientific community. Besides this, the scientists studied structural models that physically represented composite plates and panels' behaviour when submitted to specific efforts and instabilities. They wrote several papers on buckling, post-buckling, failure criteria, flutter, and post-flutter in laminated panels.

P.F.Jordan [1] was the first to identify the phenomenon in German V-2 bombs and study its physical nature. Dowell and Bismarck wrote papers [2] [3] and books [4] [5] dealing with obtaining the stability boundaries and the post-flutter behaviour in metallic panels used in aircraft and rockets using the Galerkin Method and the Finite Elements Method, respectively.

Several authors, such as Sawyer[6] and Gray and Mei[7], analyzed the stability frontiers in composite materials. Sawyer obtained the critical dynamic pressure in symmetrical two, four and six-plies laminates for square glass-epoxy, graphite-epoxy and boron-epoxy laminates with the fiber direction angle varying from $[\theta, \theta]$, $[\theta, \theta, \theta, \theta]$ and $[\theta, \theta, \theta, \theta, \theta, \theta]$ (all symmetrical). He obtained the highest critical pressure when the fibers were aligned with the flow regardless of the number of layers. Mei and Gray obtained the critical dynamic pressure and its limit cycle oscillation (LCO) for one-ply square composite plates as the lamination angle varied (15º, 45º and 90º). Some authors, such as Abdel-Motaglay, Chen and Mei [8], Mei, Abdel-Motaglay and Chen [9] and Shiau and Lu [10], studied the effect of structural non-linearity in composite laminates presenting their LCO.

Tsai [11, 12] analyzes the behaviour of composite used in most projects: the laminate that is known as a quad. He compares its characteristics and behaviour with a new double-double (DD) laminate. His analysis involves its behaviour concerned with homogenization, saving the weight of the composite and improving quality and simplicity in addition to its better performance. York [13] applied quad and DD laminates to analyze buckling and compared your results. Zhao et al. [14] present the advantages of the DD laminates compared to quad, mainly with homogenization. As the quad must have symmetry to the middle plane, this thickness would be greater than the DD, causing difficult homogenization and increasing its weight.

The approach of most researchers who have studied the behaviour of composites in flutter is to study the behaviour in different directions and increase the number of layers trying to obtain the best laminate. This work studies the behaviour of a laminate that is easy to manufacture and widely used, the quad or quadaxial laminate, and compares it with the classical approach.

2 Methodology

The equation governing the panel flutter was obtained using the Hamilton Principle is:

$$\int_{t_0}^{t_2} \delta(T-U)dt + \int_{t_0}^{t_2} \delta W dt = 0 \tag{1}$$

where $T = \frac{1}{2}\int_A \rho_m h(\frac{\partial w}{\partial t})^2 dA$, h is the thickness and ρ is the material density. The bending strain energy, due to small deformations to orthotropic plates [3], can be expressed as:

$$U = \frac{1}{2}\int_0^a\int_0^b [D_{11}(\frac{\partial w}{\partial x})^2 + D_{22}(\frac{\partial w}{\partial y})^2 + 2D_{12}\frac{\partial^2 w}{\partial x^2}\frac{\partial^2 w}{\partial y^2} + 4D_{33}(\frac{\partial^2 w}{\partial x \partial y})^2 + 4D_{13}\frac{\partial^2 w}{\partial x \partial y}\frac{\partial^2 w}{\partial x^2} + 4D_{23}\frac{\partial^2 w}{\partial x \partial y}\frac{\partial^2 w}{\partial y^2}] \tag{2}$$

The work done by the quasi-steady aerodynamic forces [3]:

$$W = -\int_A \frac{2q}{V\beta}(V\frac{\partial w}{\partial x} + \frac{M^2-2}{M^2-1}\frac{\partial w}{\partial t})w dA \tag{3}$$

with $q = \frac{\rho V^2}{2}$ known as dynamic pressure, $\beta = \sqrt{M^2-1}$, V is the free stream velocity, M é o Mach number of free stream and ρ is the air density. The equation of work can be simplified to quasi-steady aerodynamic forces to high Mach number:

$$W = -\int_A (\frac{2q}{M}\frac{\partial w}{\partial x} + \frac{2q}{VM}\frac{\partial w}{\partial t})w dA \tag{4}$$

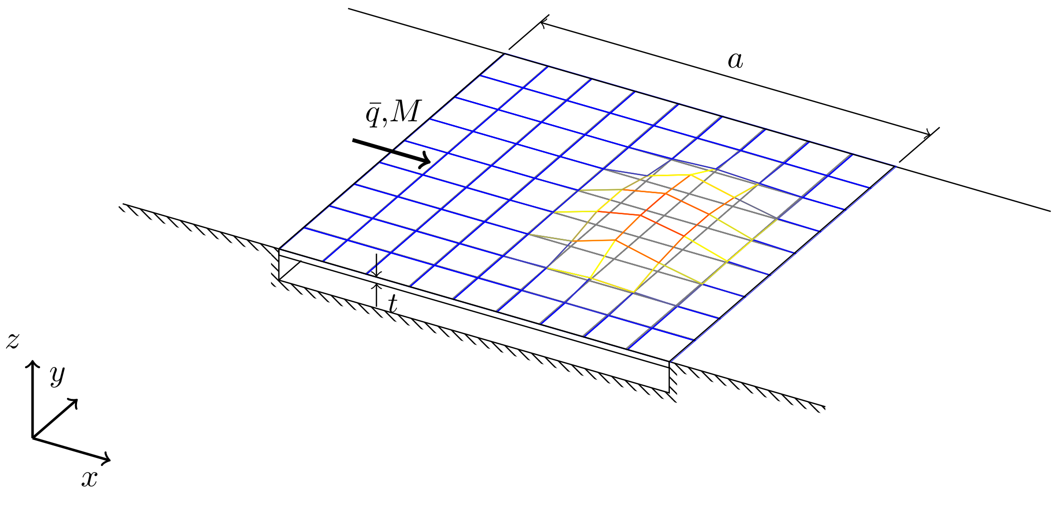

Figure 1. Panel flutter model of a square plate [15].

The problem stated is illustrated in Figure 1 and it is composed of a square panel of thickness h and of length a, subjected to supersonic flow at a given Mach number M and dynamic pressure q. Dividing the plate into finite elements and writing each element for $w = [N]\{q^e\}$, one $\{q^e\}$ is the vector of the nodal degrees of freedom, and [N] is the matrix of the interpolation functions [16]. Applying $w = [N]\{q^e\}$ in the Hamilton Principle and minimizing the functional:

$$[K^e]\{q^e\} + [m^e]\{\ddot{q}^e\} + g[a_1]\{\dot{q}^e\} + [a_2^e]\{q^e\} = \{0\} \tag{5}$$

where $g = \frac{2q}{VM}$ and $\lambda = \frac{2q}{M}$ is a parameter of dynamic pressure.

The model is discretized into 2x2, 4x4 and 8x8 mesh elements:

$$[K]\{q\} + [m]\{\ddot{q}\} + g[a_1]\{\dot{q}\} + [a_2]\{q\} = \{0\} \tag{6}$$

. The system of equations assumes solutions of the type $\{q\} = e^{wt}\{q_0\}$, and it transforms into an eigenvalue problem. A finite element program was elaborated to obtain the limits of aeroelastic stability for plates, both metals and laminates. The program outputs are compared with Sawyer [6] with good results. The convergence test was executed, and the 4x4 mesh presented the quickest and the best results. One routine was implemented to evaluate the A, B and D matrices using the Classical Laminate Theory (CLT).

3 Results

The plate that was simulated by the program has the following properties [6]: The convergence test was

Table 1. Plate Properties

E_{11}/E_{22}	G_{12}/E_{22}	ν_{12}
10	0.33	0.3

executed for four meshes: 2x2, 4x4, 8x8 and 16x16, and the results are presented in the table below. The results were generated on a square plate, simply supported, made by glass epoxy with six plies, and the fiber angle is [0,0,0,0,0,0].

Table 2. Convergence of the outputs of the program

Mesh	λ
2x2	453
4x4	400.3
8x8	402.1
16x16	402

The program was validated when the outputs were compared with the literature [6]. The table presents the comparison of the six layers and different angle combinations. We use an 8x8 mesh For comparison.

Table 3. Validation of the model - Six Plies

angle	λ	Sawyer	dif(%)
[0,0,0,0,0,0]	402.1	400	0.5
[90º,90º,90º,90º,90º,90º]	176	175	0.57
[45º,45º,45º,45º,45º,45º]	295	300	1.7
[22.5º,22.5º,22.5º,22.5º,22.5º,22.5º]	382	370	3.2
[67.5º,67.5º,67.5º,67.5º,67.5º,67.5º]	225	205	9.7

When we analyze the differences, we can observe that when the free stream is aligned with the fibers [0,0,0,0,0,0] and when the flow is orthogonal to the fibers [90º,90º,90º,90º,90º,90º] the errors are insignificant. However, the errors increase when we compare them from different angles. Probably this is caused because when the fibers are disposed of [0,0,0,0,0,0] and [90º,90º,90º,90º,90º,90º], the components of A matrix A_{16} and A_{26} are zeros. It is probably a limitation of the program that the error increase to almost ten per cent when the A matrix has components out of the diagonal main.

When the number of layers is reduced to four layers, the results are presented in Table 4. In this table, the errors are kept constant, perhaps because we studied the 0, 90º and 45º angles of the fiber (less than 2%)

Table 4. Validation of the model - Four Plies

angle	λ	Sawyer	dif(%)
[0,0,0,0]	403	400	0.75
[90º,90º,90º,90º]	176	175	0.57
[45º,45º,45º,45º]	295	300	1.7

In the next table, we study the behaviour of the quad [0,+45º,-45º,90], hard quad [0,+45º,+45º,+45º,+45º,-45º,-45º,-45º,-45º,90º] and soft quad [0,0,0,0,0,+45º,+45º,-45º,-45º,90] and the ten plies laminate. When the results

Table 5. Comparison between laminates as Quad

angle	λ	A_{16}	A_{26}
[0,+45º,-45º,90]	451	0	0
[0,+45º,+45º,+45º,+45º,-45º,-45º,-45º,-45º,90]	476	0.0124195	0.0124195
[0,0,0,0,0,-45º,-45º,-45º,-45º,90]	455	-0.0094625	-0.0094625
[0,0,0,0,0,0,0,0,0,0]	403	0	0

are analyzed, we observe that the dynamic pressure increases by more than eighteen percent when we use the hard quad and thirteen percent in the soft quad. The reference used is the zero laminate with the same number of layers [0,0,0,0,0,0,0,0,0,0]. If we compare it with the quad four layers laminate, we can conclude that is the best because with few layers, only four, your result is so conservative as the others.

4 Conclusions

After this study, it can be concluded, from the point of view of increasing dynamic pressure, that the quad with four layers has the best results compared to others. Many improvements must be made in the program: including the non-linearities building its limit cycle (LCO), increasing the order of the aerodynamic model, studying the double-double composite and using the optimization routine.

Acknowledgements The author wishes to acknowledge the help provided by Pró-Reitoria de Pesquisa da Universidade Federal de Minas Gerais.

Authorship statement. The author hereby confirms that they are the sole liable person 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 author or has the permission of the owners to be included here.

References

[1] P.F.Jordan. The physical nature of panel flutter. *Aerodigest*, pp. 34–38, 1956.
[2] E.H.Dowell. A review of the aeroelastic stability of plates and shells. *AIAA Journal*, vol. 8, n. 3, pp. 385–399, 1970.
[3] M.N.Bismarck-Nasr. Finite element analysis of aeroelasticity of plates and shells. *Applied Mechanics Reviews*, vol. 45, n. 12, pp. 461–482, 1992.
[4] E.H.Dowell. *Aeroelasticity of Plates and Shells*. Noordhoff International, Leyden, Netherlands, 1975.
[5] M.N.Bismarck-Nasr. *Structural Dynamics in Aeronautical Engineering*. AIAA, Reston, Virginia, USA, 1999.
[6] J.W.Sawyer. Flutter and buckling of general laminated plates. *AIAA Journal*, vol. 14, n. 4, pp. 387–393, 1977.
[7] C.E.Gray and C.Mei. Large amplitude finite element flutter analysis of composite panels in hypersonic flow. *AIAA Journal*, vol. 31, n. 6, pp. 1090–1099, 1993.
[8] R. K.Abdel Motagly and C.Mei. Nonlinear flutter of composite panels under yawed supersonic flow using finite elements. *AIAA Journal*, vol. 37, n. 9, pp. 1025–1032, 1999.

[9] K. M. C.Mei and R.Chen. Review of nonlinear panel flutter at supersonic and hypersonic speeds. *Applied Mechanics Reviews*, vol. 52, n. 10, pp. 321–332, 1999.

[10] L.Shiau and L.Lu. Nonlinear flutter of two-dimensional simply supported symmetric composite laminated plates. *Journal of Aircraft*, vol. 29, n. 1, pp. 140–145, 1992.

[11] S. A. J.D.D.Melo. S.W.Tsai and R.Rainsberger. *Composite Laminates: Theory and Practice of Analysis, Design and Automated Layup*. Stanford University, Stanford, CA, 2017.

[12] ´S.Tsai. Double-double: New family of composite laminates. *AIAA Journal*, vol. 59, n. 11, pp. 4293–4305, 2021.

[13] ´C.B.York. Laminate stiffness tailoring for improved buckling performance. *Thin-Walled Structures*, vol. 161, n. 107482, pp. 1–13, 2021.

[14] A. S. C. D.Kennedy. ´K.Zhao and X.Liu. Defining the design space for double-double laminates by considering homogenization criterion. *AIAA Journal*, pp. 1–14, 2023.

[15] V.Silva and H.A.Pegado. Panel flutter investigation including thermal effects through the fem. *Cilamce 2022 - Foz de Iguaçu,PR,Brazil*, 2022.

[16] M.N.Bismarck-Nasr. On the sixteen degree of freedom rectangular plate element. *ComputersStructures*, vol. 40, n. 4, pp. 1059–1060, 1991.