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MINIMIZATION OF VIBRATION IN AERONAUTICAL WING SPARS UNDER FLUTTER SITUATION

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Abstract. This research project aims to investigate the mitigation of vibrations in the spars of aeronautical wings during flutter occurrences. The study will delve into aeroelastic phenomena, particularly focusing on flutter, defined as the self-excited interaction of vibration modes within a modified system, which can potentially lead to catastrophic failures. An analytical method has been developed to compute the flutter velocity, considering the stiffness and mass matrices, and the utilization of a Tuned Mass Damper (TMD) has been proposed to enhance the flutter velocity, thereby extending the aircraft's operational range. Suggestions for future research directions have been provided.

1 INTRODUCTION

In the present study, we will investigate the flutter phenomenon in an aeronautical wing. The typical translation of the word "flutter" from English to Portuguese is "draping," describing the motion that flags exhibit when stirred by the wind. Similarly, this phenomenon occurs in aeronautical wing structures when the relative air displacement reaches a critical velocity threshold. To mitigate this effect and enhance the relative displacement speed of an aircraft, we will design a Tuned Mass Damper (TMD). As demonstrated later, this device can expand the range of velocities before flutter occurs. Subsequently, we will outline the three primary topics encompassed in this investigation.

2 VIBRATIONS

Dynamics, rooted in Newton's laws, pertains to the interaction of forces applied to bodies, leading to displacements. Structures, being bodies, respond to forces by generating inertial forces. Structural analysis adheres to the scientific method: observation, hypothesis formulation, testing, analysis of results, test repetition, and conclusion. Testing involves

constructing a mathematical model with solutions grounded in the laws of mechanics. A one-degree-of-freedom model characterizes systems controlled by a single coordinate. Common models encompass undamped free vibrations and damped vibrations, with equations of motion derived from Newton's second law. These equations can be solved either analytically or numerically.

2.1 Damped Free Vibrations

The mathematical model of the spring-mass system depicted in Figure 1 adheres to the principles of mechanics. Upon application of a horizontal force P(t) to the mass, the spring reacts with an elastic restoring force proportional to the displacement (u) and a damping force proportional to the velocity $\dot{u}$.

Like, this,

$$f_i = P(t) - f_e - f_d, \tag{1}$$

which, rearranged, falls into the well-known form of the Equation of Motion of a one-degree-of-freedom system, the ordinary differential equation (ODE):

$$M\ddot{u} + C\dot{u} + Ku = P(t). \tag{2}$$

A case of interest is when the system is free, that is, without the external force P(t), and without damping, where the equation falls back on that shown in Eq. (3). In this case, the only possible movements are due to the initial displacement conditions, , and speed, . The EDO becomes.

$$M\ddot{u} + Ku = 0, \tag{3}$$

Where

$$\omega = \sqrt{\frac{K}{M}} \tag{4}$$

is the undamped circular frequency of the system (in rad/s, in SI). The cyclic frequency (in Hz, or cycles per second) is

$$f = \frac{\omega}{2\pi}, \tag{5}$$

whose inverse is the period of free vibration (in seconds),

$$T = \frac{1}{f} = \frac{2\pi}{\omega}. \tag{6}$$

What is being said is that when the structure is put in motion, it will vibrate harmonically

with frequency, that is, it will repeat the movement that number of times in each second. The period is the time interval between the peaks of this movement. Both frequency and period are properties of the structure and are called “natural”.

This harmonic response, dependent on the initial conditions, can be written as

$$u(t) = \rho\cos(\omega t + \theta) \tag{7}$$

Considering the presence of damping, as is necessary in real structures, we have the ODE

$$M\ddot{u} + C\dot{u} + Ku = 0, \tag{8}$$

Or

$$\ddot{u} + 2\xi\omega\dot{u} + \omega^2 u = 0, \tag{9}$$

The solution to the ordinary differential equation (ODE) is:

$$u(t) = e^{-\xi\omega t}\rho\cos(\omega_D t + \theta), \tag{10}$$

Note that the resultant harmonic motion (Figure 1) experiences a rapid decline in amplitude owing to the negative exponential term it multiplies, while its frequency is slightly diminished by damping. Consequently, the corresponding period is slightly extended.

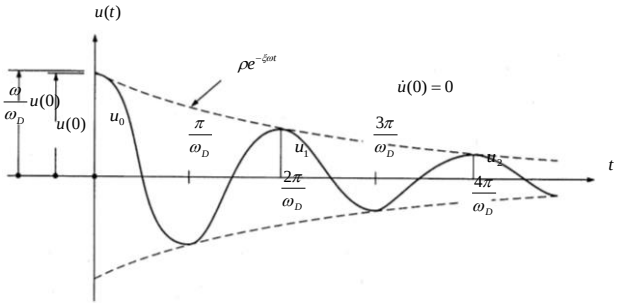

Figure 1 - Response to free vibration of a system with subcritical damping

In the context of flutter, which is the central focus of this study, it essentially represents a damped free system. However, an instability phenomenon arises wherein, contrary to the diminishing displacements observed in Figure 4, there is a progressive increase in displacement. This escalation in displacement can potentially lead to the system's failure.

3 FLUTTER

Flutter is a self-excited vibration in which an elastic body immersed in a flow gains energy from the fluid, resulting in continuous oscillations determined by the body itself. It's a natural response, unlike forced vibrations like resonance. Aircraft structures, due to their flexibility, experience various distortions under load, known as aerelasticity, leading to problems like flutter, buffeting, and dynamic response. Flutter, the most studied aerelastic phenomenon, occurs when two or more vibration modes couple, leading to unstable oscillations. The critical flutter velocity is reached when damping becomes zero. Cantilevered aircraft wings experience

flutter due to coupling of torsional and translational degrees of freedom. Solving flutter problems can be done in time or frequency domains, with frequency domain methods being computationally efficient.

3.1 The Flutter Equations

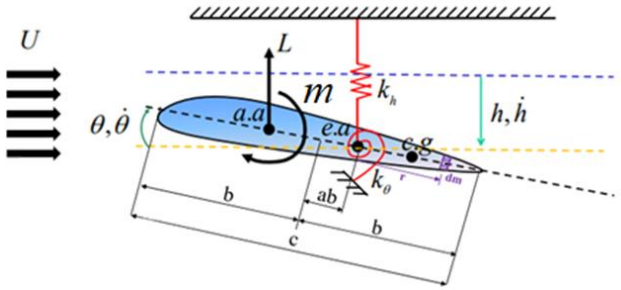

Figure 2 - Representation of the variables involved

Using the equations of Lagrangian mechanics, in the model shown in Figure 2, one can develop the free vibration equation, with two degrees of freedom, given by (Cardoso, 2022).

$$\begin{bmatrix} M & -Mb(a-e) \\ -Mb(a-e) & I_p \end{bmatrix} \begin{bmatrix} \ddot{h} \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} k_h & qSC_{L\theta} \\ 0 & k_\theta \end{bmatrix} \begin{bmatrix} h \\ \theta \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \tag{11}$$

is the dynamic air pressure, r is the air density, S is the area of the airfoil section, and is a dimensionless variable that describes the position of the center of gravity as a function of b and CLq is the slope of the lift coefficient curve as a function of the angle of attack q.

Equation (11) can be rewritten matrixly as

$$M\ddot{u}+Ku=0 \tag{12}$$

Where, M is the mass matrix, K the stiffness matrix, $\ddot{u}$ the acceleration vector and u the displacement vector.

To determine the natural frequencies of vibration of the system, the following eigenvalue problem is solved:

$$\det(\boldsymbol{K} - p^2\boldsymbol{M}) = 0 \tag{13}$$

When it reaches a so-called critical value, instability occurs. The solution to equation (13) is given by:

$$p_j = d_j + \omega_j i \tag{14}$$

where dj is the real component and wj the imaginary component of the complex roots.

$$u(t) = e^{d_j t}(cos\,\omega_j t + isen\omega_j t) \quad (15)$$

The imaginary component ω_j i of Equation 14 generates a harmonic oscillator in Equation 15. When dj is zero, simple harmonic motion occurs. But when dj becomes non-zero, flutter can occur. If dj is negative, damped free vibration occurs.

4 TUNED MASS DAMPER

A Tuned Mass Damper (TMD) is a system engineered to diminish vibration amplitudes by absorbing kinetic energy. It comprises a mass-spring system adjusted to the primary structure to attenuate oscillations. Integration of a TMD alters the system's frequencies, thus enhancing dynamic performance and preventing resonance. In flutter scenarios, the objective is to maximize the critical speed, enabling higher-speed operations with reduced displacements. Design parameters for TMD entail the natural frequency ratio between TMD and primary structure, as well as the mass ratio. The TMD dissipates energy through vibration, thereby decreasing the amplitude of structural motions. This study focuses on employing a TMD to alleviate flutter-induced vibrations in an aircraft wing spar, thereby broadening the operational speed range of the aircraft.

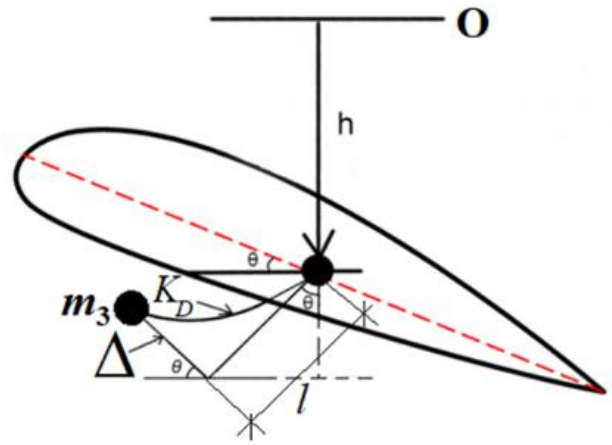

Figure 3 - Model including the TMD

To develop the TMD matrices, being the stiffness and mass matrices, one must first find the values of the stiffness of the TMD rod (KD) and the equivalent mass at its end.

$$K_\Delta = 3\frac{EI_\Delta}{l^3} \quad (16)$$

The mass of the TMD (MD):

$$M_\Delta = \frac{\rho_\Delta l}{4} + m_3 \quad (17)$$

The kinetic energy (T) of the TMD is given by:

$$T = \frac{1}{2} M_D\,(\dot{v}^2 + \dot{u}^2) \quad (18)$$

Thus, using the equations of Lagrangian mechanics, one can find the TMD mass matrices (MD).

$$\boldsymbol{M}_{\Delta} = \begin{bmatrix} M_{\Delta} & 0 & 0 \\ 0 & M_{\Delta} l^2 & M_{\Delta} l \\ 0 & M_{\Delta} l & M_{\Delta} \end{bmatrix} \tag{19}$$

And using Hooke's Law, the TMD stiffness matrix is determined to be

$$\boldsymbol{K}_{\Delta} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & K_{\Delta} \end{bmatrix}. \tag{20}$$

Adding these matrices with those already obtained for flutter, we have

$$\boldsymbol{M} = \begin{bmatrix} M + M_{\Delta} & -Mb(a-e) & 0 \\ -Mb(a-e) & I_p + M_{\Delta} l^2 & M_{\Delta} l \\ 0 & M_{\Delta} l & M_{\Delta} \end{bmatrix} \tag{21}$$

And

$$\boldsymbol{K} = \begin{bmatrix} k_h & qSC_{L\theta} & 0 \\ 0 & k_{\theta} & 0 \\ 0 & 0 & K_{\Delta} \end{bmatrix}. \tag{22}$$

With the matrices M and K described above, the optimization of the TMD design is undertaken, the formulation of which will be presented in the subsequent section.

5 OPTMIZED TMD DESIGN

For the TMD project, an optimization problem was defined, as follows. Determinex∈R^3, onde x = [x1 x2 x3]T = [U hD MD]T, that minimizes the functionf(x) = - x1,

Subject to

g1 = -|$l1 - l2$| + $e \leq 0$
g2 = -|$l2 - l3$| + $e \leq 0$
g3 = -|$l1 - l3$| + $e \leq 0$
g4 = -D_b + e ≤ 0
g5 = $m_D - m_{lim} \leq 0$

where hD is the height of the cross-section of the TMD, li, i = 1,2,3 are the problem eigenvalues of |K - lM| = 0, e is a small number (equal to 0.1) to force convergence, Db is the radicand of Bhaskara's formula for calculating l2 and l3, mD is the ratio between the mass of the TMD and the mass of the main structure and mlim is the threshold value of mD, equal to

0.05. The optimization problem then consists of maximizing the value of the critical flutter velocity.

6 RESULTS OBTAINED

This chapter presents the results obtained from the conducted studies, employing an aeroelastic model of an airfoil. In this model, the spar comprises a rectangular section fabricated from a composite material, while the TMD is constructed from aeronautical aluminum. The adopted data include:

a = -0.15.
b = 0,127 m;
e = 0,25;
M = 4,7174 kg;
Ip = 1,543 kg.m2;
kh = 16282 N/m;
kq = 5816 N.m/rad;
K12 = 2,93 U2;
ED = 70 GPa; (modulus of elasticity of the TMD material)
rD = 2600 kg/m3; (TMD material density)
bD = 30 mm; (base of the TMD cross section)
l = 130 mm. (TMD rod length)

The ultimate design of the TMD, employing the GRG (Generalized Reduced Gradient) method, yielded x = [21.63 m/s 0.178 mm 0.236 kg]T. Consequently, by computing the eigenvalues of the problem |K - lM| = 0 and determining the natural frequencies of vibration, the graphs depicted in Figures 4 and 5 were generated.

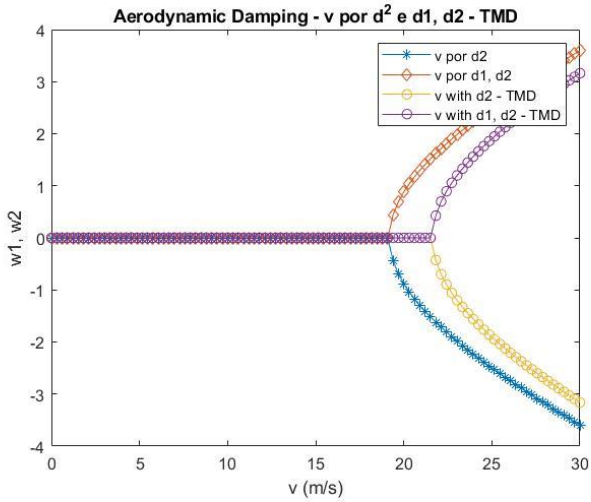

Figure 4 - Graph of aerodynamic damping with and without TMD

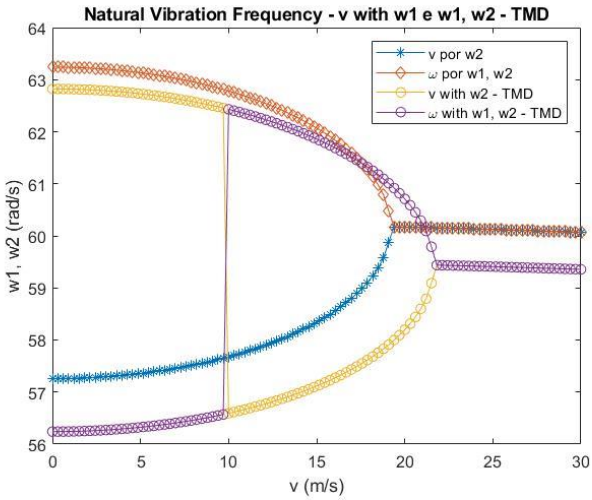

Figure 5 - Graph of the natural frequency of vibration without TMD

It can be seen in Figures 8 and 9 that TMD increased the critical flutter velocity from 19.18 m/s (without TMD) to 21.63 m/s, that is, a 13% increase in the range of possible flutter velocity. aircraft operation. The result shows that the TMD can be very useful for the design of aircraft spars.

7 CONCLUSIONS

The flutter phenomenon was mathematically modeled following the theory proposed by Cardoso (2022). Stiffness and mass matrices were constructed for a two-degree-of-freedom model, with the introduction of a third degree of freedom associated with the TMD. In this study, the TMD was depicted as a flexible rod integrated into the primary structure.

Two scenarios were examined to illustrate the structural behavior under flutter conditions: one without the TMD and the other with the TMD installed. The results demonstrated a 13% increase in the aircraft's operational speed range with the implementation of the TMD.

Consequently, it was concluded that employing TMD can significantly enhance the design of aircraft spars by extending the operational range. For future research endeavors, it is recommended to explore different types of TMDs using time domain analysis, imposing constraints on dynamic displacements, and setting a lifespan for the structure, even during an instability process.

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