Comprehensive aeroservoelastic evaluation of a simplified rectangular wing subjected to parametric control analysis

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Abstract.

The quality of aircraft flight control systems plays important role in terms of aircraft guidance, but especially in safety, integrity and stability. Furthermore, such systems enable the response when an external load, such as gust, reaches the aircraft. The control strategies have become increasingly important in the aeronautical context, especially in the aeroelastic field when, in addition to inertial, elastic and aerodynamic interaction, control surfaces can be excited in such a way as to impair aircraft performance or even prevent undesirable aeroelastic phenomena. With the increase in geometric complexity, availability of lighter materials with high equivalent stiffness, it is also necessary to update and implement computational tools for aeroservoelastic analysis to ensure not only efficiency and cost reduction in testing and certification processes but also enable the advent of new technologies. Thus, this work aims to perform an aeroservoelastic analysis in open and closed loop in a pre-defined geometry related to a simplified wing in order to compare the control laws usually applied aircraft's control. The model will be represented numerically as a cantilever, untapered and unswept wing, with equations of motion obtained from Lagrange energy methods for various assumed modes of vibrations. The material used in the wing will be linear and orthotropic. The aerodynamics considered will be equivalent to the non-stationary Theodorsen model, including Hanckock simplifications. The control laws will be variations of the PID method, under which various parametric combinations will be involved. The results will be presented in terms of the classic Vgf diagrams, where it is possible to identify the critical *flutter* speed. For gust behavior, temporal displacement graphs and spectral density functions will be studied. Still through ASeS, it will be possible to perform parametric comparisons, highlighting which factors influence the most in aeroservoelastic stability, making the poper initiative consolidate as an excellent preliminary aeroelastic design tool.

Keywords: *Flutter*, PID Control, Aeroservoelasticity, Control Law (up to 5 keywords)

1 Motivation and context

Control laws emerged in response to the demand for systems that exhibit enhanced response speed, reduced energy consumption, and heightened precision. Some control laws are particularly well-suited for applications in flight control systems. Some examples are PID[1], LQR([2] and MPC([3]), with PID being the most used in the industry for being simpler and presenting a satisfactory performance for most applications([1]). LQR is more used in the academic environment for its greater precision, seeking an optimal response. When introduced to the aerospace market, systems have a focus on saving fuel consumption, contributing to the agendas of zero carbon emissions in aviation by 2050 and with the economic and competitive viability of aircraft.Comfort is a determining factor in an aircraft, since comfort can be associated with safety when it comes to this niche, allowing faster responses to gusts to which the aircraft is susceptible during its operation, for example.

Aeroelasticity is the field of aerospace engineering that examines the interplay among inertial, elastic, and aerodynamic forces, which can interact and give rise to undesirable aeroelastic phenomena ([4],[5]. Aeronautical structures possess flexibility and, when subjected to aerodynamic forces, typically experience deformations such as bending, twisting, or a combination thereof. These deformations alter the aerodynamic flow, and to a certain extent, they can absorb energy and potentially lead to structural failure ([6], [7]. In this context, it is also essential to address these effects while considering the control forces applied to the aircraft's control surfaces, which are crucial for aircraft control and guidance. Control laws are important to ensure safety and minimize risks for institutions and companies, ensuring compliance with internal and external acts, regulations, norms and laws.

The wing model employed in this study is derived from the model put forth by Wright and Cooper ([1]). This model encompasses a clamped, rectangular 3D wing, incorporating a control surface at the trailing edge. The mass distribution is uniform, and a Proportional and Derivative (PI) control model is assumed to tackle the aeroservoelastic problem and explore parametric variations and their impact, with the aim of mitigating or delaying flutter and gust effects.

A variation of control gain values, as well as changes in control surface size, and stiffness based on bending and torsion frequencies, is carried out to analyze how these parameterizations interact with flutter speed.

A project is underway at the University of Brasília - FGA to develop an open-source platform for flutter analysis. The project aims to investigate how control laws can extend the flutter speed, enabling aircraft to operate at higher velocities even with reduced stiffness coefficients (flexible wings). The application of control systems to manage aeroelastic phenomena is referred to as aeroservoelasticity or active control

2 Control System PID

Also known as a three-term controller, the PID Controller has applications in various areas, such as system electronics, autopilots, ships, and industrial robots. Its popularity is due to its simple structure and robustness in many applications, as well as the familiarity of engineers and technicians with the PID algorithm due to its easy implementation. As a result of its already discussed characteristics, it is used for introduction to the world of control systems ([8]).

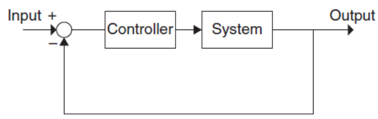

Figure 1. Closed loop system with a forward controller and a unity feedback loop:[1]

The most commonly used type of control strategy typically sets the controller of the system in Figure 1 as linear multiples of the error E (proportional) along with its integral (I) and derivative (D) multiplied by some gain values. Hence the proportional-integral-derivative (PID) controller can be written as:

$$h_{PID}(t) = K_p E + k_i \int E dt + K_d \frac{dE}{dt}, \tag{1}$$

Where Kp, Ki, Kd are the proportional, integral and derivative gains. In the Laplace domain this becomes

$$H(s) = K_p + \frac{K_i}{s} + k_d s \tag{2}$$

There are various empirical schemes that can be used for setting the three gain values, buttuning of the gains often still has to be executed in order to get optimal performance. The proportional term determines the speed of the response, the integral term improves the accuracy of the final steady state, while the derivative term helps to stabilize the response.

State feedback control typically used the set-up in Figure 2 with the controller feedback equal to –Kx. Such an approach leads to optimal control techniques (Whittle, 1996), which specify that the gain matrix K is such that some cost function is minimized.

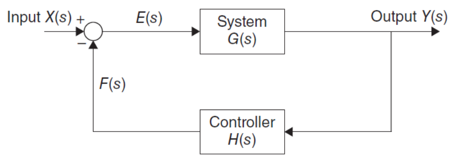

Figure 2. Closed loop system with controller in the feedback loop:[1]

Within the field of aeroservoelasticity, particularly in the analysis of flutter, both open-loop and closed-loop systems play pivotal roles. Open-loop analysis involves the examination of an aircraft's structural behavior without the influence of control inputs, enabling the identification of critical flutter speeds and modes. In contrast, closed-loop analysis takes into account the impact of control laws and feedback mechanisms on flutter. It delves into how control systems, actively mitigate or delay flutter oscillations, thereby enhancing the aircraft's stability and safety during flight. A comprehensive understanding of both open-loop and closed-loop characteristics is fundamental for a thorough evaluation of flutter phenomena within the realm of aeronautical engineering.

3 ASE - Aeroservoelastic Model

The model utilized in this study is derived from the framework presented in [1], which is established through the application of Lagrange's energy equations for motion, as detailed in [9]. This model relies on three assumed mode shapes for bending and torsion, and the unsteady aerodynamic model employed is founded on the Hancock's approximation method, [10]. From this panorama, it is possible to define the ASE problem as Eq.3.

$$\begin{bmatrix} m\frac{sc}{5} & m\frac{s}{4}(\frac{c^2}{2}-x_f c) \\ m\frac{s}{4}(\frac{c^2}{2}-x_f c) & m\frac{s}{3}\left(\frac{c^3}{3}-x_f c^2+x_f^2 c\right)\end{bmatrix}\begin{Bmatrix}\ddot{q}_b\\ \ddot{q}_t\end{Bmatrix}+\left(\rho V\begin{bmatrix}\frac{cs}{10}a_w & 0\\ -\frac{c^2 s}{8}b_w & \frac{-c^3 s}{24}M_{\dot\theta}\end{bmatrix}\right)\begin{Bmatrix}\dot{q}_b\\ \dot{q}_t\end{Bmatrix}+ \\ +\left(\rho V^2\begin{bmatrix}0 & \frac{cs}{8}a_w\\ 0 & -\frac{c^2 s}{6}b_w\end{bmatrix}+\begin{bmatrix}\frac{4EI}{s^3} & 0\\ 0 & \frac{GJ}{s}\end{bmatrix}\right)\begin{Bmatrix}q_b\\ q_t\end{Bmatrix}=\rho V^2\begin{Bmatrix}-\frac{ca_c s}{6}\\ \frac{c^2 b_c s}{4}\end{Bmatrix}\beta \quad (3)$$

.

This can be expressed briefly as Eq.4,

$$\mathbf{A}\ddot{\mathbf{q}}+(\rho V\mathbf{B}+k_v\mathbf{F})\dot{\mathbf{q}}+(\rho V^2\mathbf{C}+k_d\mathbf{G}+\mathbf{E})\mathbf{q}=\mathbf{0} \quad (4)$$

where the inertia matrix is represented as (**A**), aerodynamic damping is denoted as (**B**), aerodynamic stiffness as (**C**), and structural stiffness as (**E**). Additionally,the control matrices **F** and **G** proportionally related to the displacements and velocities of the model, as anticipated by the PI model.

The wing geometry data are shown in table (1) (1)

4 Results and Discussions

After an exhaustive literature review, the Matlab and Simulink platform was utilized, incorporating a three-degrees-of-freedom wing model defined by parameters described mathematically. Simulink assumed a pivotal role in the construction of a block diagram for simulating the PID system. Subsequently, following the successful operationalization of the code and validation, the parameterization of variables with notable influence on the wing's flutter-related behavior was carried out. The results that ensued are presented herein. The physical and geometric parameters utilized by Wright and Cooper 2015, as well as those additionally described in this study, are detailed in the Tab. 1.

Table 1. System's numerical data for simulation. [1]

Parameter	Value
Semi-span (s)	7.5 m
Chord (c)	2 m
Elastic axis (x_f)	0.48c
Mass axis (x_{cm})	0.5c
Mass per unit area	$100kg/m^2$
Bending Rigidity (EI)	$3\times10^7 Nm^2$
Torsional Rigidity (GJ)	$5\times10^6 Nm^2$
Lift curve slope (a_W)	2π
Non-dimensional pitch damping derivative (M_θ)	-1.2
Air density (ρ)	1.225 kg/m^3

The first result brings the comparison between a system with control law gain equivallent to kv=0.02. It is seen that the open-loop system has a flutter at 145 m/s, while in closed-loop the vibration is delayed to 165 m/s. Similarly, one can observe the phenomenon of delay in the graph of the roots of the eigenvalues.

4.1 Parametric variation of the k_v

The variation of k_v, the gain by speed, was conducted while keeping k_d, he gain by displacement, at zero. During the aircraft design process, a mission profile is established. Through parameterization, we can scrutinize the performance characteristics of the conceptual design and make informed trade-off decisions that enhance safety while significantly reducing costs.

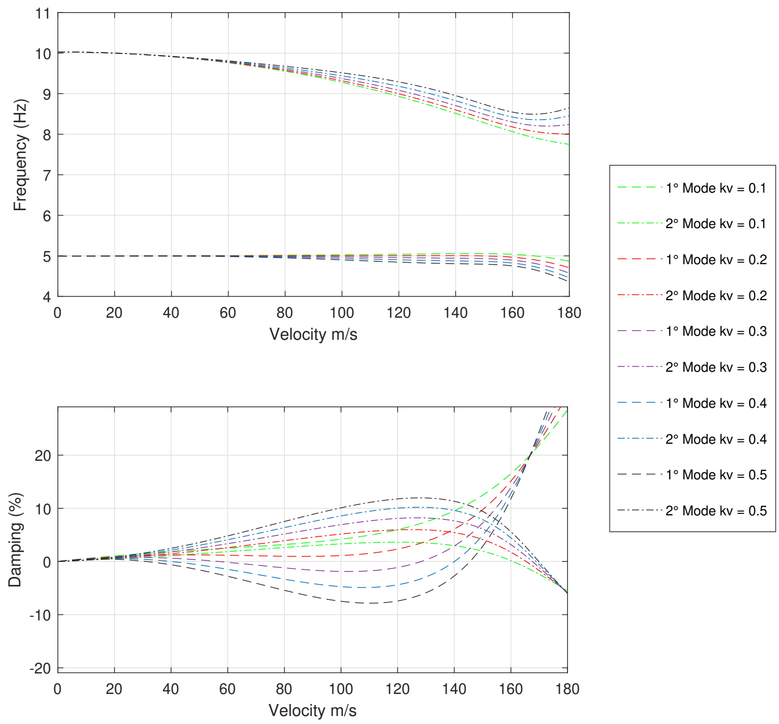

Figure 3. Behavior of the aeroelastic system given the derivative gain variation from the controller

Table 2. Relação K_v - Speed Flutter

K_v	Open Loop Speed Flutter (m/s)	Closed Loop Flutter (m/s)
-0.01	145	161
-0.02	145	165
-0.03	145	167
-0.04	145	169
-0.05	145	170

Analyzing the table, we see that for a gain equal to zero we have the same result that would be for an open-loop system as expected [8], for the negative gains as already interpreted for the reference graphs we have a delay in the path to the critical damping which increased the flutter speed, we had an acceleration in the path of the critical damping with positive values.

4.2 Parametric variation of the k_d

Currently, parameterization is performed using proportional gain, denoted as k_d, keeping k_v at zero. After simplifying the aeroservoelastic model with regard to its aerodynamic representation, varying it over the frequency domain.

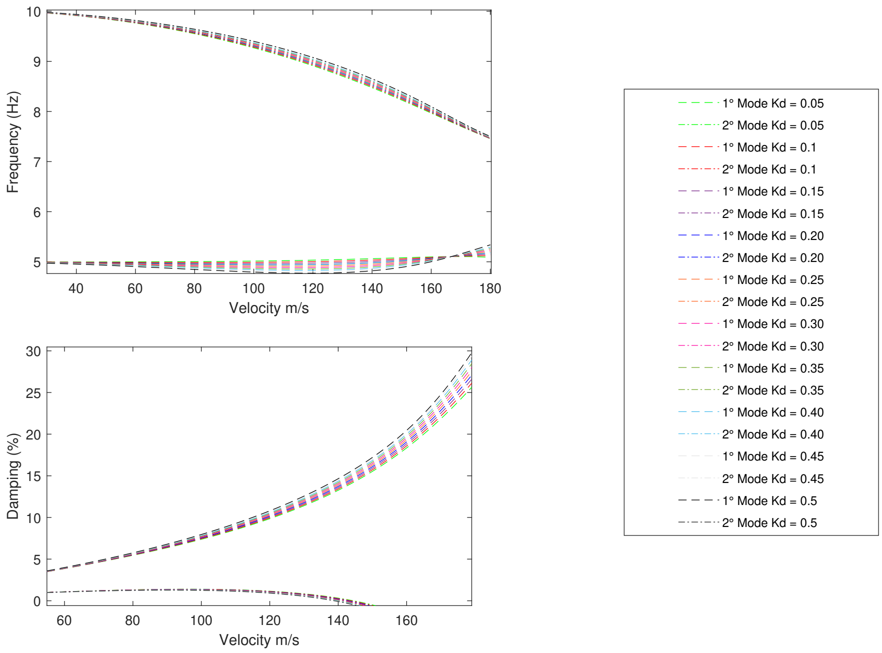

Figure 4. Behavior of the aeroelastic system given the proportional gain variation from the controller

Table 3. Relation K_d - Speed Flutter

K_d	Open Loop	Closed Loop Speed Flutter (m/s)
0.05	145	147
0.1	145	148
0.15	145	149
0.20	145	150
0.25	145	151
0.30	145	152
0.35	145	154
0.40	145	155
0.45	145	156
0.50	145	158

It is possible to observe that with the increase of k_d we have a decrease in the velocity of the flutter damping curve as a function of the critical velocity, which we can observe is of paramount importance because with the increase in the gain of the module k_d the velocity is reduced, becoming inferior to those without a control surface.

4.3 Control Surface Size Variation

The size of the control surface was varied based on the fraction of the chord formed by the control surface, k_v = - 0.05. The size of the control surface is given by the percentage of the chord in our hline, that is, for a smaller hline we have a larger control surface and for a larger hline a smaller control surface.

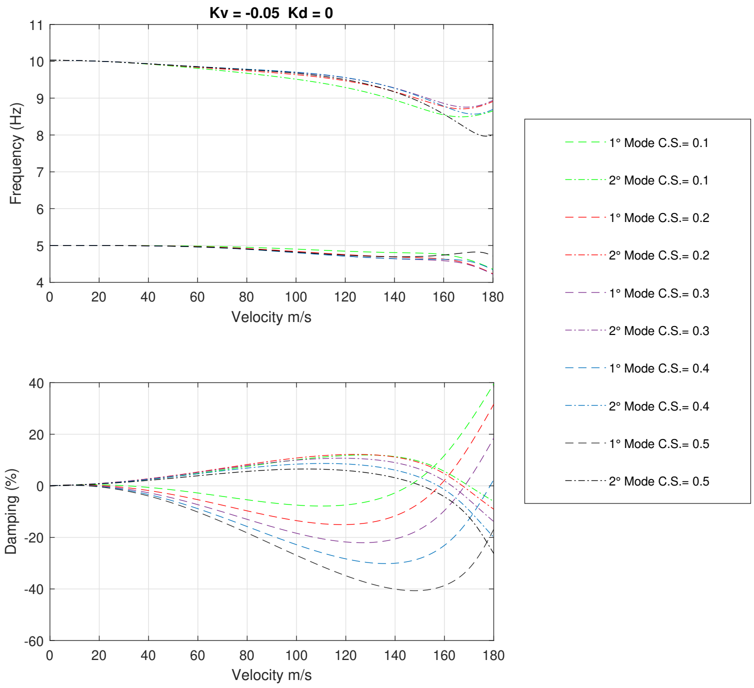

Figure 5. Root for Speed

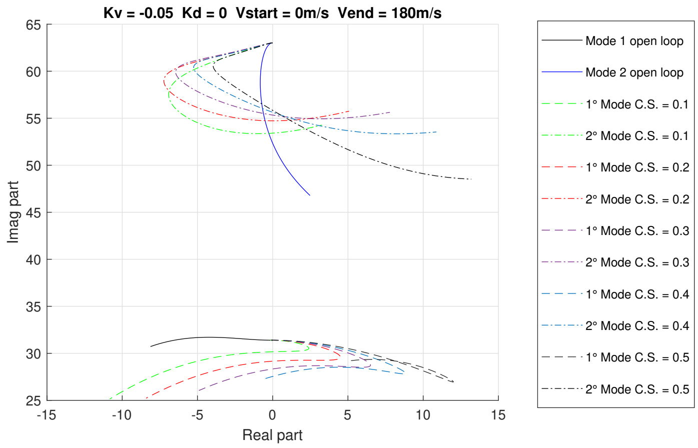

Figure 6. Root locus for open and closed loop.

We can observe how the increase of the control surface decreases the flutter speed, which makes sense because with the control surface we can increase the wing area, increasing the lift for lower speeds, we can see an increase in frequency.

Table 4. Relation K_v and Critical Velocity of flutter

Control Surface size variation (fraction of chord)	Open Loop	Closed Loop (m/s)
0.1	145	170
0.2	145	168
0.3	145	163
0.4	145	158
0.5	145	151

5 Conclusions

The study outlined in this paper has proven to be exceptionally versatile when it comes to aiding decision-making in the realm of conceptual project development. This versatility is of great value to aerodesign teams and aircraft design enthusiasts. While the model upon which these results are based may be simplified, it still provides sufficient information for making preliminary design choices. Furthermore, it's adaptable enough to incorporate the capabilities of emerging technologies and initial scientific conjectures. In the analysis of parametric performance, it becomes evident that increasing the module of gains for k_v (negative signal) enhances the aerolastic capabilities of the system, effectively postponing flutter conditions.

With the increase of the control surface area, a decrease in the flutter speed was observed due to the increase of lift on the structure, with the increase of forces on the wing as a result of the area increased by the control surface. Therefore, for a control surface to be well designed, it is necessary to analyze the stresses and vibrations on it, because each situation that the aircraft goes through will generate new loads, which can cause accidents with poorly sized aircraft. In this case we end up losing stiffness in the structure.

While acknowledging the model's limitations, the framework introduced in this context serves as a valuable instrument. Its potential can be further amplified through the incorporation of diverse control law models, the integration of nonlinear elements, and the adoption of more comprehensive structural and aerodynamic modes. These enhancements aim to mitigate or delay aeroelastic instabilities within aeronautical systems.

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