Unraveling Aircraft Flutter: The Role of Structural Actuator Saturation in Aeroelastic Instabilities

Abstract. This article presents a new concept that can be used to explain the physical mechanism that causes flutter: the concept of the structural actuator and the effects of its saturation on the aeroelastic stability of an aircraft. One detailed physical mechanism that could be the cause of aflutter, that occurred during the numerical simulation of an aircraft, is presented. Each aeroelastic mode consists of torsional and rotational movements. These two movements in each mode were dissociated and the amplitude and phase of each movement were analyzed along with the damping and frequency of the mode. The structural resistances of torsion and bending, as well as the bending movement itself, have a damping effect and torsion has an destabilizing effect on the oscillations (if the centre of pressure is ahead of the flexural axis). After a certain speed, bending becomes out of phase with the applied forces. At this point, the bending has an amplifying effect on the oscillations and only the structural stiffness dampens the movement. From the speed at which the bending movement is out of phase with the applied aerodynamic loads, the damping of the mode decreases with speed, until flutter occurs. One possible physical explanation for this sudden change of phase in bending can be attributed to the structural uncapacity to follow the higher frequency movements demanded on the structure. The real movement has an rate lower than the commanded. This difference can cause an gain and phase variation, similar to ones that occurs in actuators of flight control surfaces when they arrive on the onset frequency. Considering the structural wings are seen as physical actuators that moves the aerodynamic surfaces, if the phase difference comes close to 180 deg, the bending becomes one destabilizing movement, that is amplified with the airspeed. This causes a decreasing on the damping ratio until the flutter occurs. This idea is detailed presented in this paper.

Keywords: aeroelasticity, strain based formulation, flexible airplane, flutter mechanism, structural actuator

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1. Introduction

The term aeroelasticity designates the field of study interested in evaluating the interactions that are established between the disciplines of aerodynamics, elasticity and dynamics (Wright & Cooper, 2007). The multidisciplinary nature of this field can be synthesized by the prediction of the forces acting on the structure by using the aerodynamic theories, the deformations being predicted by the elasticity and the dynamics introducing inertial forces in the system (Hodges&Pierce, 2011). Inside the field of dynamic aeroelasticity, one of the phenomena that carries most attention is flutter. This phenomenon is considered one of the most relevant in aeroelastic studies and one of the most difficult to predict (Garrick & Reed III, 1981). Fig. 1 presents the flutter that occurred in one unmanned aircraft (Saemeil, 2007).

Fig.1 - Flutter during one flight demonstration – unmanned aircraft (Saemeil, 2007).

In recent years, environmental issues have encouraged the development of new aircraft configurations (Singh, 2021; Energy Central, 2024; Gipson, 2022).The emergence of new technologies, such as the growing use of composite materials in the aeronautical industry, which allows for the construction of aircraft with lower structural weight, and the need for specific missions, which require greater wing span, has allowed for the development of aircraft with greater structural flexibility.In these aircraft with greater structural flexibility, a coupling can be seen between the natural modes of flight dynamics and the structural modes. Modeling and understanding the flight dynamics and aeroelasticity of very flexible aircraft is a current research topic (Cesnik, 2023; Palacios &Cesnik 2023).In addition to these challenges, there has been the need of designing aircraft with new configurations. (Knowledge of) aeroelastic effects has become more important for the development of new and safer aircraft (Österheld*et al.*, 2000).

These challenges mentioned require advances in our ability to predict and mitigate (harmful) aeroelastic phenomena, even at the design stage. This requires better aeroelastic aircraft modeling capabilities, as well as a better physical understanding of the mechanisms that cause aeroelastic phenomena. Particularly for new aircraft configurations, there are limited design insights and guidelines (Riso, 2024). This increases the need for greater modeling capability and a physical analysis and understanding of the mechanisms of aeroelastic phenomena, particularly flutter.

The aeroelasticity of each aircraft is influenced by the aerodynamic, structural and mass distribution properties of the aircraft components. The aerodynamic properties are function of the aircraft's geometry and the structural properties are function of the geometry and materials used.

Despite the knowledge acquired during the last century, on aeroelastic response, on controlling this response, and also on the coupling between aeroelasticity and flight dynamics of very flexible aircraft, the physical mechanism that produces the aeroelastic phenomenon called flutter has not yet been presented in detail in the literature (from the authors' point of view).

According to Bisplinghoff and Ashley (1975), the insights that aeroelasticity specialists have are largely mathematical. Although it was pronounced almost fiftyyears ago, it is not common to find a detailed physical explanation that links the mathematical models with the physics of the problem. Generally, the approaches that use eigenvalues to find the instability are focused on plotting frequency and damping ratio charts (Wright & Cooper, 2007). None of the actual analysis methods allows a clear, and detailed physical interpretation of what is happening. Although some efforts and insights have already been developed to explain the physics involved in flutter (Biot& Arnold, 1948; Rheinfurthn&Swift, 1965; Bisplinghoff& Ashley, 1975; Patil, 2001), these works do not incorporate the data that can be extracted from eigenvectors, i.e., phase and amplitude. Only the mode shapes are usually plotted in aeroelasticity analyses. Bisplinghoff& Ashley (1975) have already mentioned that mode shape and **phase variations** play a fundamental role in the physical mechanism, since these changes have a great influence on how and where the instability of a system with multiple degrees of freedom begins, but they did not explore in details the use of eigenvectors to explain the flutter mechanism. The new approach presented by Siqueira *et al*., (2019, 2024) considered the data of eigenvalues and eigenvectors to diagnose what is happening on the structure. These analyses show an initial development that was made for an aeroelastic mode, found in a numerical model of a highly flexible aircraft, that exhibited flutter. This was the first step in supporting future analysis aimed to develop a new way of analyzing flutter. The analysis commonly performed in which the different modes are considered is called here as intermodal analysis. The analysis commonly performed not always considers what happens “inside” the mode. The separation and quantification of bending and torsion deformations allows one deeper and detailed analysis. This type of analysis is called here as intramodal analysis. This is not intended to replace the current forms of analysis that have been developed over the century and which have produced satisfactory results. The intention is simply to present a new way of analyzing the aeroelastic stability of aircraft and to achieve a better physical understanding of the flutter mechanism.

Siqueira *et al.* (2024) verified that the flutter occurred due to phase diference on the bending movement. This concept will be presented here again. The contribution of this paper is a possible explanation for occurring this phase difference. In order to explain that, two important concepts will be presented. First concept: The displacements can occur as a response to an actuator, which receives the aerodynamic loads as an input and produces the structural deformations as output. In other words, the flexible wing structure can be considered and modeled as an physical actuator. Second concept: The structural actuator saturation can cause phase differences on structural strain response. These strains occur due to aerodynamic loads, that are the input to this structural actuator.

To explain the concept of structural actuator saturation, and how it can produce a difference in phase (of the structural deformation), an analogy will be made with aircraft control surface actuators, such as elevator actuators.

When deflections and/or rates greater than the actuator can handle are commanded, the desired response for the aircraft will not be met and instabilities may occur. Example: If the elevator control is commanded to change the attitude angle, the desired and commanded attitude angle may not be reached, and in some situations pilot induced oscillations (PIO) may occur, which are a form of instability.There are different classifications and causes of PIO. PIO that occurs due to saturationin the actuator and/or at its maximum actuation rate is classified as PIO - CAT II. One criterion used to analyze this type of PIO is the OLOP (Open Loop Onset Point) criterion, which will be discussed briefly in this article.These ideas will be described in more detail throughout the article.

The concept proposed here of explaining the difference in the bending movement phase due to saturation in the structure response, considered here as an actuator, can be applied to other aeroelasticity studies. It should be emphasized that this concept of **seeing the structure as an**

actuator that responds to aerodynamic loadsis new in the literature, in the authors's knowledge.

Another concept known in the literature is to use control systems, made up of control laws and actuators, to artificially increase the aeroelastic stability of systems. There has been related research including the ones published by Micheli, (2022a) that studies active flutter suppression, and that considers actuator saturation (2022b). Gao & Cai, (2018) investigated the design of the controller stabilizing the wing flutter system, which is robust against actuator faults, actuator saturation, time delay, parameter uncertainties and external disturbances. The insights gained from actuator saturation can be applied immediately to the design of control systems and external actuators used to delay the rate at which flutter occurs.There are other ways of hindering the occurrence of flutter, such as those described by Hareesha, &Rudresh, (2022).

Although there has been research into the use of actuators and active control to mitigate aeroelastic effects, in this article **the idea related to actuator is different: to visualize the structure itself as if it were an actuator, with maximum actuation rates**. It **is important to note the difference in concepts**.In this article, the concept of **considering the wing structure as if it were an physical actuator**, which responds to aerodynamic loads and produces structural deformations, is called a **structural actuator.**

This paper is organized as follows: Section 1 presented the introduction, Section 2 presents the NFNS_s methodology, that was used on the airplane modeling and in the numerical simulations performed, Section 3 presents briefly the analyzed aircraft, Section 4 presents the concepts related to the Open Loop Onset Point (OLOP) (Duda, 1995, 1998), and used to evaluate aircraft susceptibility to PIO – CAT II. Section 5 presents the results and analysis, mainly the phase difference on the wing bending and its consequences, Section 6 presents a possible explanation for this difference in the bending phase, Section 7 presents some additional theoretical concepts and explanations, and Section 8 presents the conclusions.

2. NFNS_ methodology and equations of motion

The methodology NFNS_s (**N**on Linear**F**light Simulation – **N**on Linear **S**tructural Dynamics, **s**train based formulation) was developed by Cesnikand his co-workers (Brown, 2003; Shearer, 2006;Su&Cesnik, 2008). NFNS_s uses a beam formulation to capture nonlinearities of the structural deformations and is also capable to compute large deformations and inertial coupling between elastic and rigid generalized coordinates (Shearer, 2006; Su, 2008, Ribeiro, 2011). This methodology is also known as Strain Based Formulation. The set of coupled flight dynamics and structural dynamics equations is described in details by Brown, (2003); Shearer, (2006); Su, (2008); Ribeiro, (2011); and Sousa, (2013).

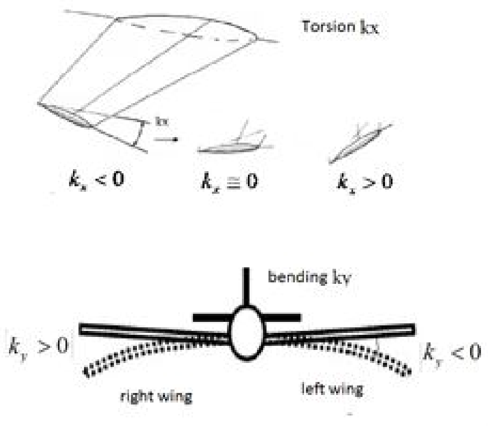


Fig.2 – Structural deformations (bending ky and twist kx) (AEROSPACEWEB, 2000, Sofla, et. Al., 2010, Sousa, 2013)

Fig.2 present the type of structural deformations presented in each element: The bending ky and the torsion kx.

3. Airplane model

The numerical platform Aeroflex (Ribeiro, 2011), was adapted in Sousa (2013) for modeling a medium size jet airplane with similar properties to Embraer EMB-190/195 and Boeing 737-200/300. The Aeroflex uses the methodology NFNS_s **(N**onlinear **F**light Dynamics– **N**onlinear **S**tructural Dynamics- **s**train based formulation).

The aircraft model presented here is the same presented in Sousa et.al., (2017), but with two differences: the wing flexural axis is located at 75% mean aerodynamic chord and the structural stiffnesses are six times lower. Fig.3 presents the aircraft plan view and the aerodynamic plan view, and structural elements of wing and horizontal tail. There are five structural elements on each wing, names as E1, E2, E3, E4, E5. The engines were modeled as rigid units appended on Element 2 (E2).

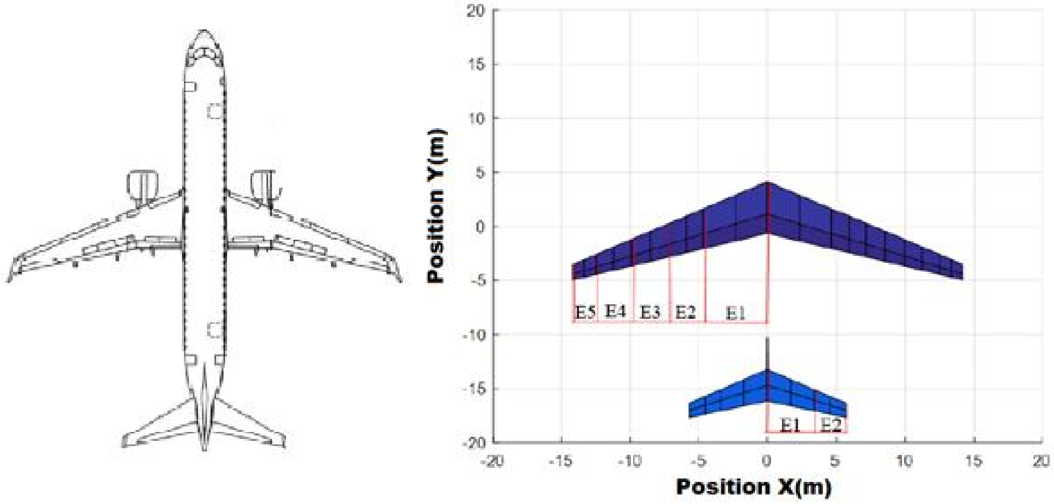


Fig.3Aircraft plan view (Doc846, w.d), and Structural elements on the wing (Siqueira, 2019)

The aeroelastic model presented is compound by the airplane geometry, aerodynamic, structural and mass distribution data. The airplane was modeled as one assemblage of beams representative of the wing and tails. The fuselage was considered to be rigid and modeled as one rigid mass appended to the airplane. The aerodynamics model considers quasi-steady loads. Quasi-steady aerodynamics was considered in order to decrease the computational cost to perform the numerical simulations. The mass was distributed along the wings, tails, engines and fuselage.More detailed parameters can be seen on Siqueira *et al*., (2024).

4. Concepts used from the flght dynamis: PIO CAT II - OLOP criteria

In this section, some concepts from the disciplines of flight dynamics and control will be presented.

Aircraft-pilot couplings (APCs) are characterized by the interactions between the pilot-vehicle system (PVS) in correspondence with the dynamics of the flight control system (FCS), being represented by benign or undesirable phenomena (National Research Council, 1997); (Hodgkinson, J. & Mitchell, D. G. , 2000).

Undesirable APC are described by rare, unintentional, and unexpected PVS oscillations or divergences, which, when they assume an oscillating temporal pattern, will be described as pilot-induced (sustained or involved) oscillations (PIOs). Undesirable APCs and PIOs are fundamentally interactive phenomena that occur during highly demanding tasks, in the course of changes in the dynamics of the environment, the pilot and/or the aircraft, which create or trigger incompatibilities between the actual and expected vehicle responses (National Research Council, 1997); (Hess, R. A.,1997) ;(McRuer, D. T., 1995).

Accidents and incidents associated with these events occur because of high-gain (demand) maneuvers, which require the pilot to have strict control(National Research Council, 1997); (Ashkenas, *et* *al.*, 1964), (McRuer, D. T., 1995) ; (Cooper, G. E. & Harper, R. P., 1969); (Gibson, J. C., 1995).Fig. 4 presents the PIO that occurred with an airplane.

Fig. 4 – Saab Gripen pilot induced oscilation (MultiplyLeadership, 2012).

PVS instabilities are characterized by quasi-linear oscillations, caused by rate saturations and/ or position limits (National Research Council, 1997); (Hess, R. A.,1997); (Ashkenas, *et al*., 1964); (McRuer, D. T., 1995); (Ossmann, D., Heller, M. & Brieger, O., 2008).

Cat. II PIO refer to severe oscillations, with amplitudes close to the intervals at which rate and/or position limits, in series with the pilot, become dominant – as primary nonlinearities, **adding amplitude-dependent phase delays** and defining the magnitude of the limiting cycle (National Research Council, 1997); (Ashkenas, et. al. , 1964); (McRuer, D. T., 1995);(Klyde, D. H.; McRuer, D. T. & Myers, T. T., 1997);(Klyde, D. H. & Mitchell, D. G. , 2004); (Liebst, B. S.; Chapa, M. J. & Leggett, D. B., 2002).

In particular, **rate saturation** has been pointed out as a recurrent cause of **sudden changes in the effective aircraft dynamics**, by promoting **additional delays in the response of the actuators, reducing the real gain and the bandwidth of the system**. The pilot, when trying to compensate for its effects, self-sustains the inadvertent oscillation, contributing to the occurrence of accidents and incidents associated with this nonlinearity.

Before continuing with the presentation of PIO concepts, it should be emphasized that flutter and PIO are different phenomena. Flutter is an aeroelastic instability, and PIO is a type of instability that occurs due to the coupling of the aircraft, its systems and the pilot. Once this information has been presented, the analogy will be shown, the central concept that can explain the sudden change of phase in the aircraft's aeroelastic response.

Many aircraft have hydraulic/electro-hydraulic actuators, which transmit the pilot's commands to the control surfaces (depth, aileron and rudder).Fig.5 present a rate limiting for a sinusoidal input (Gilbreath, 2001). The black plot presents the amplitude commanded, and the red plot presentes the real surface deflected, once the actuator is totally saturated, i.e., the rate commanded is higher than the maximum actuator rate. It can be seen that the maximum value reached by the surface (deflected by the actuator) is lower than that commanded, and that the time instant at which the maximum deflection occurs is different from the time instant at which the maximum deflection was commanded. In other words, there is a decrease in gain and a increase in phase delay. Fig.6 present a Rate Limiter Describing Function Bode plot. This function shows the decrease in gain and increase in phase difference as a function of frequency.It shows the effect of actuator saturation.Saturation only occurs after a certain frequency, called the onset point (Duda, 1995, 1998; Gilbreath, 2001).Fig.7 presents a Nichols chart: Open loop frequency response q/qc (pitch rate/ ptich rate commanded in one simulation performed (Gilbreath, 2001)). The jump in phase and gain when the actuator saturates, can be seen.

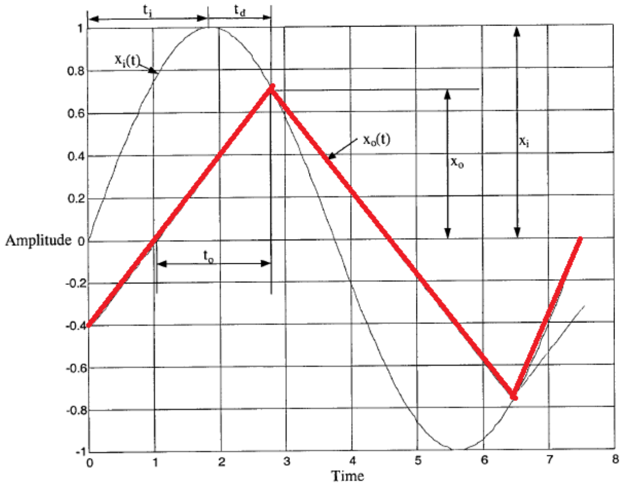


Fig.5 – Rate limiting for a sinusoida input (adapted from Gilbreath, 2001).

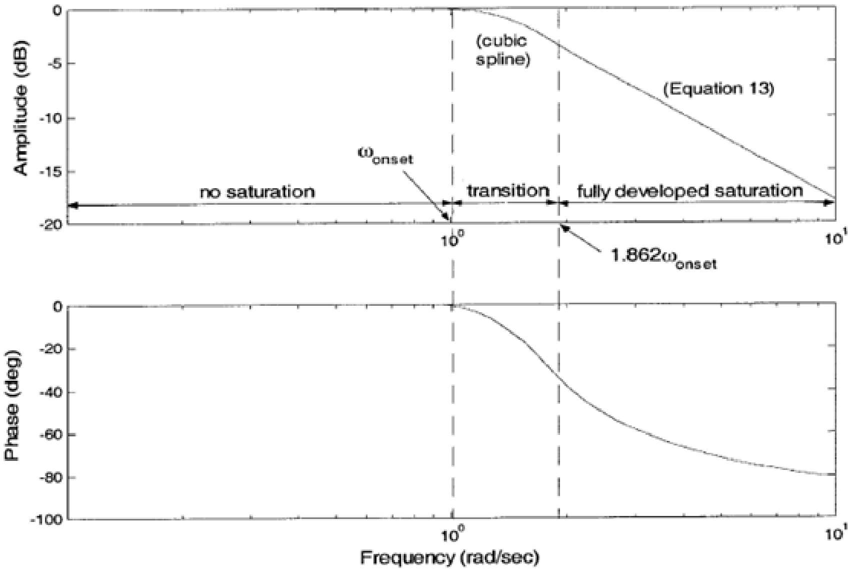


Fig. 6 – Rate Limiter Describing Function Bode Plot (Gilbreath, 2001).

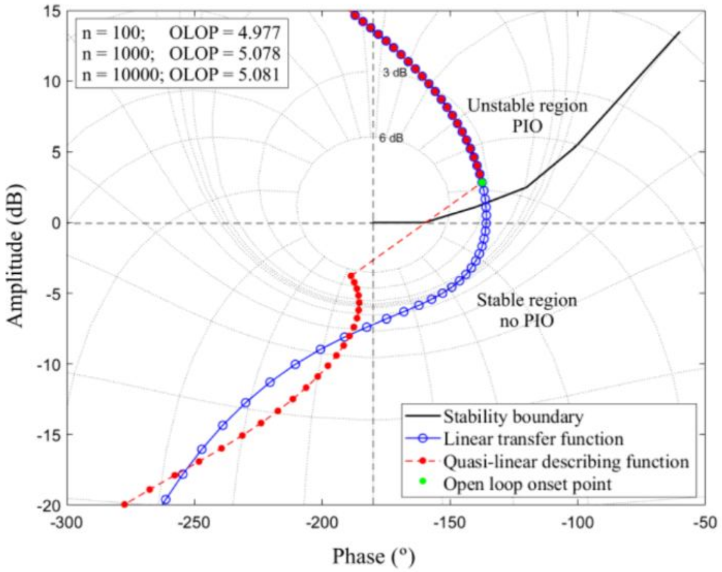


Fig. 7 - Nichols chart: Open loop frequency response q/qc

The text in this section and Fig.4 to 7 have been presented to better explain the **concept of instability caused by actuator saturation**. **<u>The main idea that will be used is that saturation in the actuator rate can produce a change in phase, and this can cause instability</u>**. In next section, the issue analyzed will be the aeroelastic response and the flutter simulated in the airplane model used by Siqueira *et al.*, (2019, 2024).

5. Results and detailed physical explanation – part 1 (phase difference on bending)

The airplane model briefly presented on Section 4, and detailed described in Siqueira, *et al.*, (2024) were used in the numerical simulations, presented here. Trimmings were made at different airspeeds, and the eigenvalues and eigenvectors were calculated for each airspeed.

With all the results obtained, it was possible to plot some graphs. The frequency and damping ratio (Fig.8) are related to the different modes (M1, M2 and M3), whereas the phase and amplitude are associated with the mode M2 and with each element at each member (wings, horizontal tail or vertical tail) (Fig.9). If a member with five elements is chosen, five phase curves will be shown in one graph and five amplitude curves in another graph.

The approach aimed to identify the flutter condition and analyze the behavior of each part of the aircraft structure.Therefore, simulations with a highly flexible aircraft were performed. The airspeed range analyzed was between 100 and 600 m/s. More than 50 aeroelastic modes were obtained, but just three are presented. So, the three first aeroelastic modes were selected for the physical analysis. Fig.8 shows the frequency and damping ratio of these three modes analyzed.

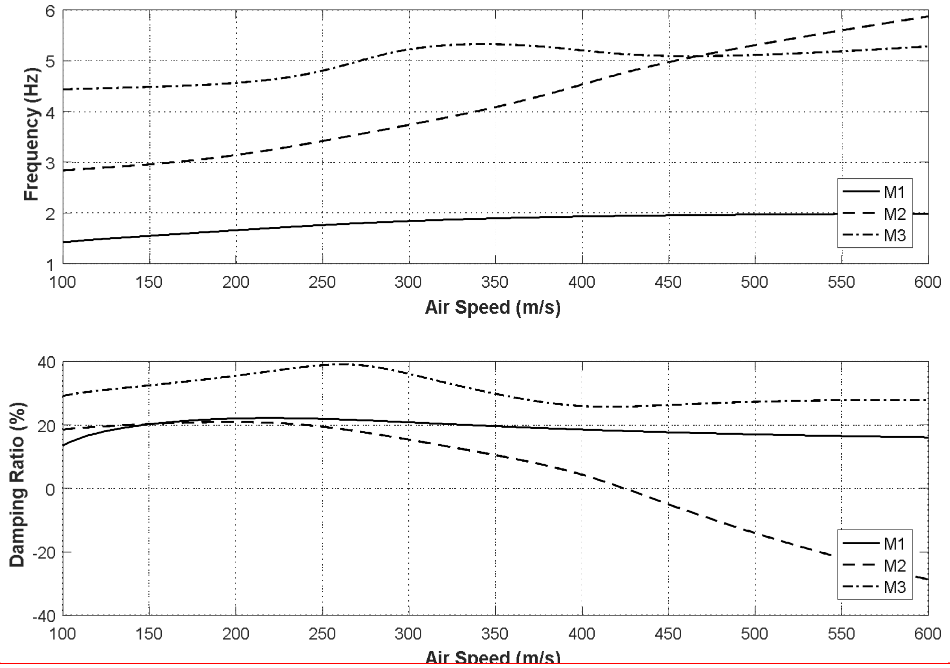


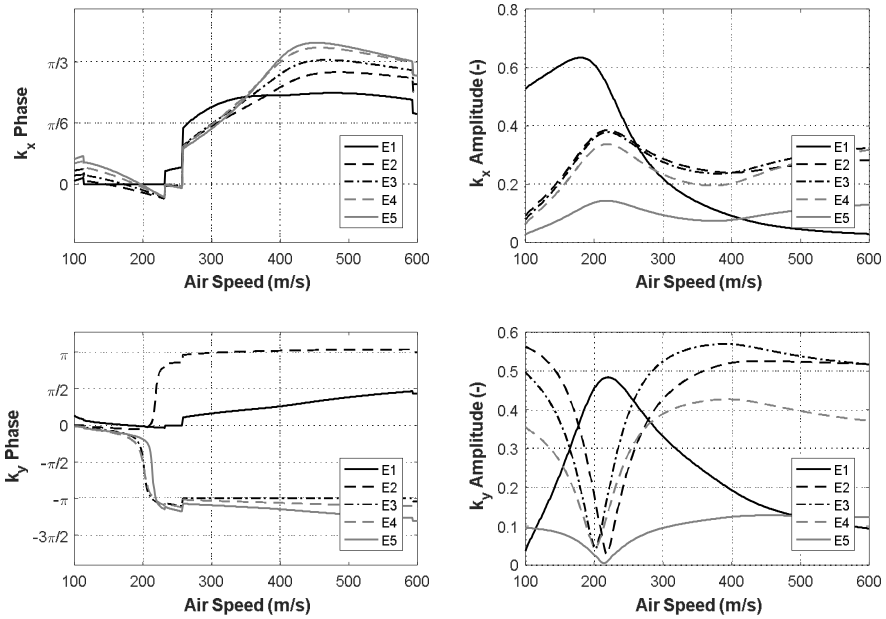
Fig.8 - Frequency and Damping Ratio of the aeroelastic modes.

It is clear from Fig.8that the second mode, M2, is the one that has negative damping ratio and, consequently, flutter. Since this mode is the one which presented flutter, the intramodal analysis was totally focused on it. Fig.9 shows the amplitudes and phases for both components, torsion kx and bending ky, for mode 02 and specifically for the right wing, what is analogous to the left one. There are five curves in each chart because each wing is composed of five elements. Element 1 is the first wing element attached to the fuselage. Element 5 is on the wing tip, and Elements 2, 3 and 4 are intermediary (See Fig.3). The engine is attached to the Element 2 (Siqueira, 2019).

Based on Fig.9(a), it is noted that the phase values of torsion depart slightly above zero in ascending order and tend to have the same negative phase value (around -10º). When this value is reached, there is a small leap around 225 m/s and a moderate one near to 250 m/s. After these leaps, the values were increased until the flutter velocity, around 425 m/s. The curves of torsion amplitudes have the same behavior among themselves and increase the values until 225 m/s. Reaching the maximum, the torsion amplitudes started to decrease until the flutter airspeed.

The bending phases, shown in Fig.9(c), began around 0º and had a sudden variation of 180º around 200 m/s, the same velocity in which the minimum amplitude value was achieved. The bending phase values had a considerable changing and presented a smooth variation after the rapid changing. The element 01 did not present this variation, possibly because this element is attached to the fuselage. The element 02 had a different behaviour when compared with the elements 03, 04 and 05, what can be explained by the presence of the engine in this element (Siqueira, 2019, Sousa, 2017).Fig.9b and Fig. 9d present the relative amplitudes or torsion and bending, respectively.

The flutter is characterized by the signal change in the damping ratio (positive to negative). This is equivalent to say that a signal change occurs in the corresponding eigenvalue.



Fig,9: (a) Phase for torsion kx, (b) amplitude for torsion kx (b),
(c) phase for bending ky, (d) amplitude for bending ky.

It is evident by intramodal analysis that the torsion and bending presented a phase difference. Phase difference plays a fundamental role in the amount and direction of energy flux between the aerodynamic flow and the structure (Patil, 2001). This means that the mismatch between bending and torsion creates conditions for a flutter. Before presenting more results, it would be convenient to remember some basic physical concepts, that can be useful. Once the airplane receives one external aerodynamic perturbation, some aerodynamic forces and moments can be produced. Example: gusts produce modifications on the wing lift force. This modification on lift force (called here as delta lift force) can produce structural deformations as wing bending and torsion. If the bending deformation has one phase difference smaller than 180 deg, the wing will bend Up, and if the twist has one phase lower than 180 deg, the wing will twist Up (leading edge Up). The consequence is different angles of attack, that will change the lift force.If the wing bending is Up, the local angle of attack will decrease, and the wing lift also (See Fig. 10). In Fig.10, the downward deflection of the aileron has produced an increase in lift force which is not shown in the figure. The wing will bend upwards because of the change in lift. This upward bending will produce a change in local flow (decrease in local angle of attack) and a change in lift force (decrease), which are shown in the figure. So, the bending reaction has one stabilizing effect (it decreases the initial variation on lift force (delta lift force), and, as consequence it can dampen the structural oscilations). The bending act as one dynamic damping. It the wing twist Up, the angle of attack will increase, and the wing lift also. So, the wing twist has one destabilizing effect, when the aerodynamic lift force is ahead/ forward than the flexural axis. The angle of attack would increase more, and so, the delta lift force.

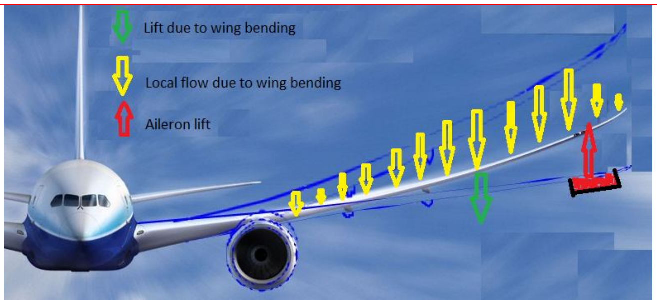


Fig.10 – Damping in external perturbations due to bending deformations (Sousa, 2013, Quora, 2016).

The situation can be different when **there are phase differences between the twist and bending** (See Fig.11). Both deformations acting together can have one destabilizing effect. The positive delta lift force due to the bending act at the same time as the positive delta lift force due to the torsion.

Before moving on, it is advisable to better comprehend the concept and meaning of phase difference. Concept: If it is considered one system under periodic perturbation, ex: sinusoidal input, the phase shows the time instant in which the system will respond to the external perturbation. This idea is commonly understood, but its meaning on aeroelastic analysis were not detailed understood during this study. If one plot of structural displacement (xo) versus the derivative of the displacement (relative to the time, vo, divided by the frequency ωn) is made, and if all the possible combinations are plotted, one circle can be obtained (Fig.11). If one point of this circle is chosen, the angle obtained is the phase. The phase presents the relation between the structural displacement, and its derivative (Inman, 2014). Its derivative vo is called here as velocity vo. Once these comments and explanations were presented, the analysis done can be presented.

With the results presented for the second mode, it is possible to begin the proposition of the flutter physical mechanism. The differences seen in the phase occurred practically at the same airspeed in which the amplitudes reach the maximum (torsion) and minimum value (bending). It is possible to subdivide the physical mechanism into two different moments: before and after the phase difference (phase leap). Each component has a velocity associated vo, which is found by the phase angle.

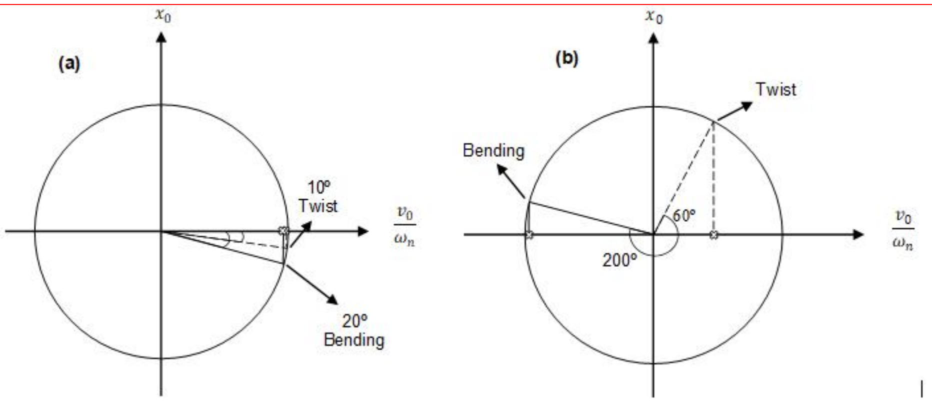


Fig. 11 - Scheme for the components (a) before the phase difference and (b) after the phase difference.

In Fig.11, the x axis presents the values of vo/ wn, where vo is the time derivative of structural displacement and ωn is the natural frequency. The y axis presents the structural displacement xo. The angle presents the phase (Inman, 2014). It is noticed by the Fig. 11(a) that initially both movements were practically in phase. Despite the similarity, there is a small "advantage" in the speed of torsion motion. That is, this movement leads the behavior of the aeroelastic mode. However, as both components are in phase, the bending stabilizing effect helps to prevent instability. But, the stability mechanism is completely changed when the phase difference occurs, which is demonstrated in Figure 11(b). The bending inverts the direction of movement (i.e., alters the phase angle in 180º) and the torsion that had a small advantage before and was countered by the stability effects, now has a minor instability effect. The magnitude of the bending speed is practically the same, but acts in the opposite direction, which physically changes the system behavior. When the lift is positive, the bending is negative. This increases the angle of attack, that increases the lift. In addition to this, the torsion component has a reduction in velocity magnitude since the phase is around 60°. The twist deformations keep maintaining one destabilizing effect, but, now the bending has also one strong instability effect. Only the structural bending and twist stiffnesses help to avoid the instability until one defined airspeed value. This stabilizing effect decreases with the airspeed increment. The damping ratio presented on Fig.8 seems to corroborate with this explanation. While the torsion acts as the mechanism to destabilize the movement, the stiffness of the structure and the aerodynamic effect produced by the bending tend to counteract the instability created. Until the phase difference occurs, the bending and torsion components move together and stability is ensured by the superiority of the bending effects. After the phase difference (phase leap), the bending starts to act in the direction of instability. The effect of instability increases with the airspeed because the delta aerodynamic force (delta lif force) created is greater than that ocurred before the phase difference. This is maintained until the moment that the structure is unable to counteract the instability, so flutter occurs.With the phase difference, a change in the structural behavior occurs, when there is a temporal lapse between the action of the force and the structure movement. The structure that previously moved upwards now is moving downwards and vice-versa. Although the movement is a combination of bending and torsion, the greater part of instability is directly associated with the bending mechanism. Fig.8 shows that the structural damping of mode 2 was approximately constant, close to the airspeed of 200 m/s and began to decrease close to 210 m/s. Fig.9 shows that the torsion phase significantly changed its value close to this speed.

6. Detailed physical explanation – part 2 ("structural actuator" saturation)

In section 5 it was shown that the discontinuity in the bending phase may have been the cause for the decrease in damping, until flutter occurred. In this section a possible cause for this sudden phase change in wing bending will be presented.Fig. 12 presents the aeroelastic interactions that occur during one airplane flight.

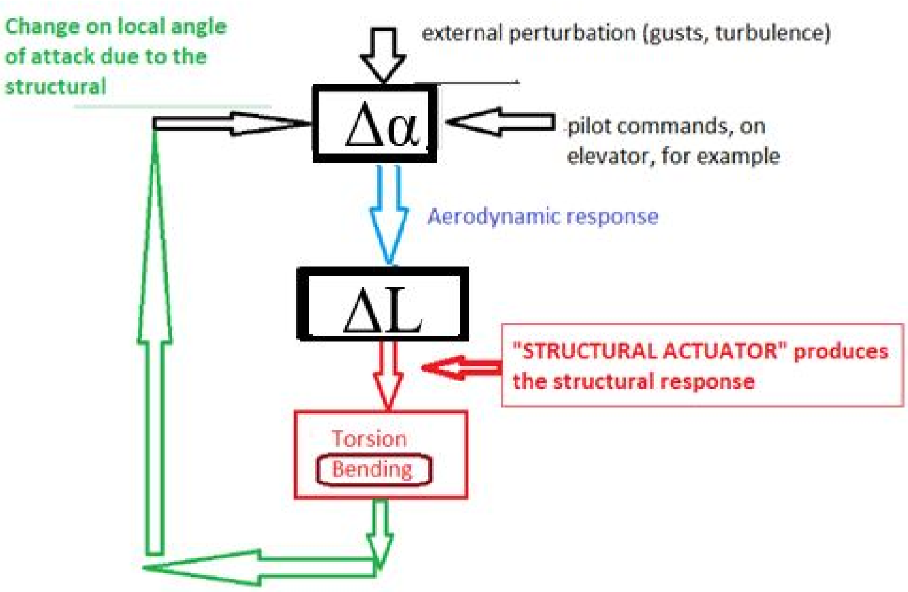


Fig. 12 – Aerodynamic and Structural Interactions and the Structural Actuator.

When there is any changle in angle of attack (Δα), caused by pilot commands, or by external perturbations, the aerodynamic lift is modified. This change on aerodynamic lift (ΔL)can cause bending and torsion moments on the wing structure. If the structure is flexible, bending (ky) and torsion (ky) deformations can occurr. This structural deformations alter the airplane geometry, and also the local angle of attack. And this change can modifiy the aerodynamic loads. The blue arrow presents the aerodynamic response and the red arrow presents the structural response. The structure behaves like an actuator, which changes the shape of the structure after receiving commands from the aerodynamic loads. We can use the expression: structural actuator.The structural actuator commands the bending and torsion strains.This innovative approach of treating structural wings as physical actuators, bridges mechanical behavior with control theory concepts.

Once the structural actuator concept has been presented, the theory presented in Section 5 can be used. If the frequency commanded to the structural actuator exceeds its limit, saturation will occur and the phase will change. This significant change may lead to the observed instability.

Fig.13 and 14 show results of time marching simulations, without flutter (Fig. 13) and with flutter (Fig. 14).

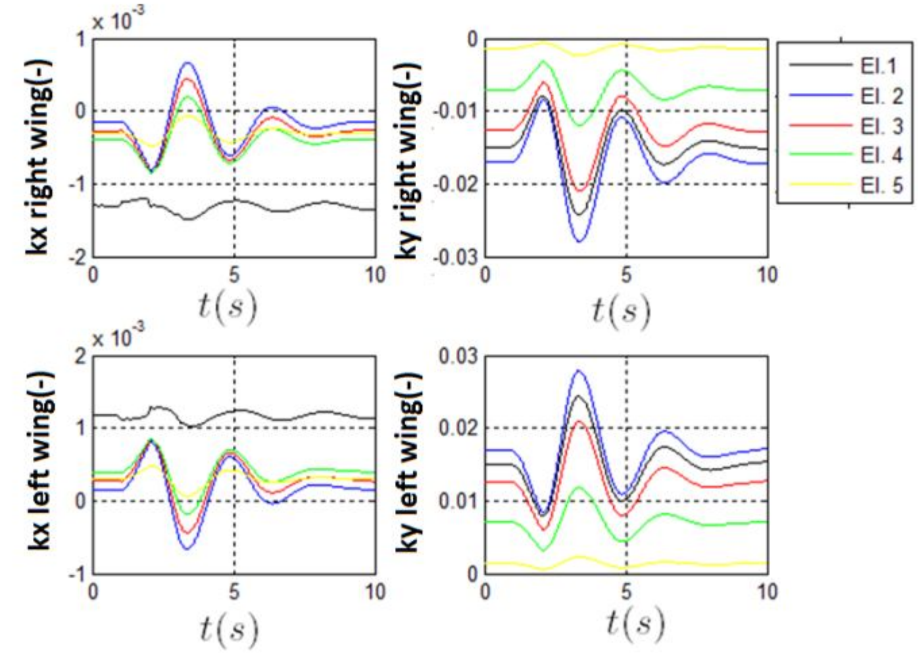


Fig. 13– Time marching simulations, without flutter (Sousa, *et al.*, 2024)

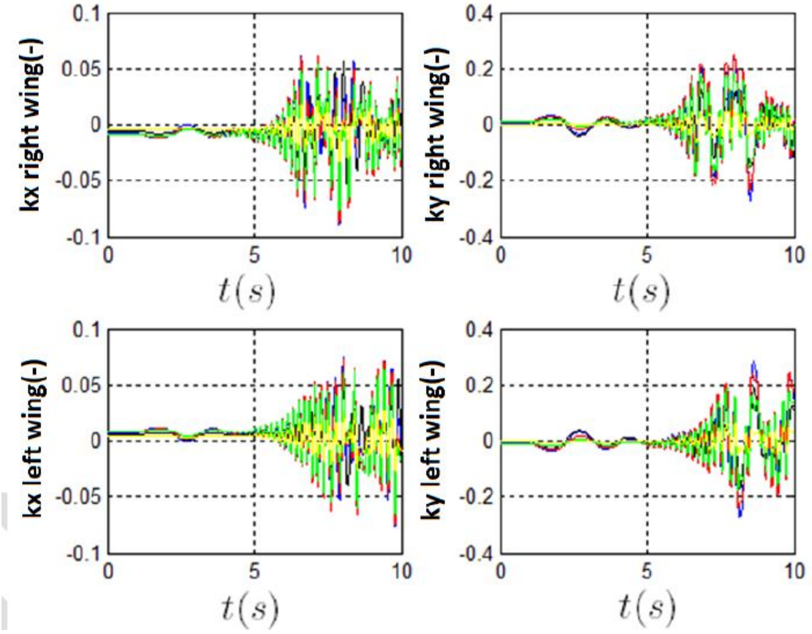


Fig. 14 – Time marching simulations, with flutter (Sousa, *et al.*, 2024)

It can be seen that there was no phase difference between the bending and torsion movements in Fig. 13. Fig.14 shows the deformations when there is flutter. In Sousa, (2024) it is shown that there was a significant phase change between torsion and bending when flutter occurred.. Fig.8 shows that there was an increase in the frequency in the M2 mode at the same time as the speed increased.

Fig.15 presents one summary of the idea proposed in this article. The Structural Actuator saturates in one specific frequency (and airspeed). This causes one great change in the bending movement, that becomes destabiling. The damping ratio begins to decrease until the flutter occurs.

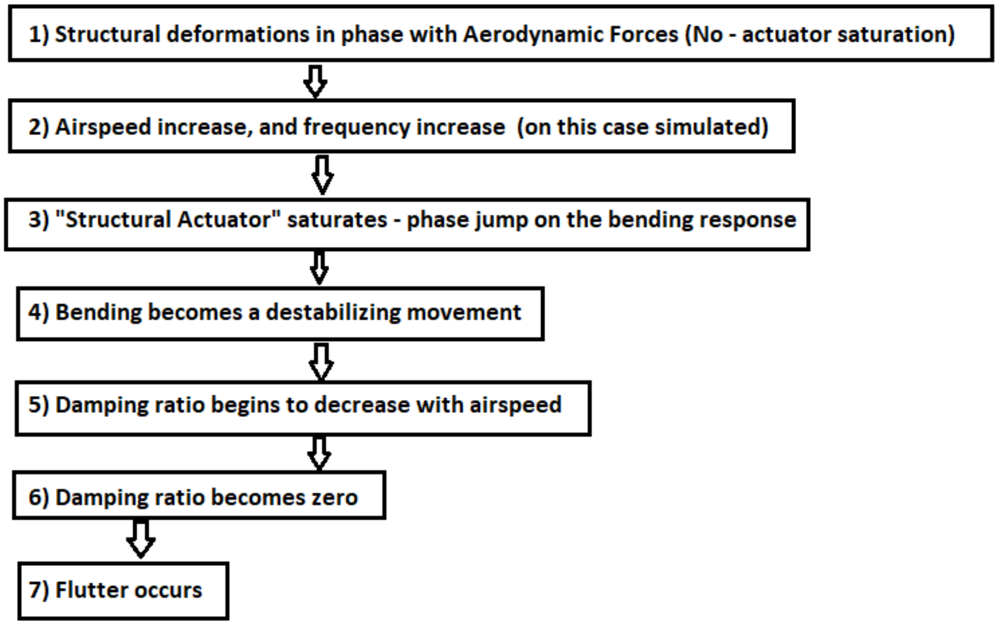


Fig. 15 – Final explanation for the flutter physical mechanism.

It should be remembered that this paper is proposing an explanation for the mechanism that caused flutter in the simulation of an aircraft. It is not intended in any way to replace the results obtained by aeroelasticity experts over the last century. However, the data and explanations presented in Siqueira (2019), Siqueira *et al.*, (2024) and here could be tested on other aircraft to see if the same explanations could be given in other situations. This fact could contribute to the validation of the physical mechanism of flutter, proposed here.

Some future researchs that could be proposed are:

a) The definition ofone equivalent actuator model capable to model the structural response as function of the aerodynamic loads.
b) To obtain the frequency saturation of this structural actuator model.
c) Visualize the effects of this saturation.
d) Calculate the energy variations during the structural deformation. Use energy concepts to explain this structural saturation.
e) Plot Bode diagrams of the bending and torsion of each element, and at different airspeeds. In these Bode diagrams, the input (on the system) would be sinusoidal signals on the aircraft angle of attack/ and or on the airplane vertical airspeed component. **This could prove the concept of**

structural actuator saturation.

7. Additional theoretical concepts and explanations

This section presents some theoretical concepts and further clarification of the results and analysis presented. Fig. 12 shows three modes, and only mode M2 showed flutter. One might wonder if the coupling of the M2 mode with the M1, M3 and other modes not shown could have contributed to the flutter. Before starting the analyses presented in in Siqueira (2019), Siqueira *et al.*, (2024) and here, it was hypothesized that only what happened in this mode could explain the occurrence of flutter. The fact that the other modes have positive damping seems to contribute to this hypothesis. Fig.8 and 9 show the aeroelastic modes obtained by trimming the aircraft at specific conditions (constant altitude and different airspeeds), linearizing around this equilibrium point and obtaining the eigenvalues and eigenvectors associated with each eigenvalue. It should be remembered that in each mode, there can be different movements with different amplitudes and relative phases. In each mode there are bending and torsion movements, which could be decoupled, even though they are in the same mode. To prove this concept, see the example 2.3.4, page 26, from Wright & Cooper, (2007). In the same eigenvector, related to the same eigenvalue, there can be different components with different amplitudes and relative phases. Also, from the discipline of flight dynamics, if the natural mode of short period is considered, this mode contain two components: angle of attack and pitch rate, with different amplitude and relative phases, but, both componentsot the same mode, with the same frequency and damping. Considering the aeroelasticity discipline: each aeroelastic mode can have different components (bending and torsion) with different amplitudes and relative phases, and with the same damping and frequency.

During the studies and research carried out to write this article, and the previous one (Siqueira, *et al.*, 2024) , some theoretical concepts about aeroelasticity were presented, but, in the opinion of the authors, they are not always explained in detail. These concepts will be recalled in this section: structural modes and aeroelastic modes. Structural modes do not consider aerodynamic forces, and do not consider structural damping, at least, in many results presented in the literature. The eigenvalues of structural modes are just the square of the mode's natural oscillation frequency, and the eigenvectors are obtained by knowing the structural stiffness and mass distribution matrices (when the structural damping is not considered). The aeroelastic modes are the same as the structural modes in the particular condition of zero airspeed, i.e. the condition in which there are no external aerodynamic forces or any other type of external force. As the speed increases, there are external forces, the equilibrium conditions are different, and consequently the state matrix and eigenvalues are also different. As a result, the eigenvectors are also different for each airspeed.

As mentioned earlier, PIO and flutter are different phenomena. Despite this, it was considered that the mechanism that produces PIOCAT II (saturation of the actuators and their rate) can be used to explain the phase difference seen in the aircraft analyzed here. If the wing structure is visualized as anphysical actuator, which produces the structural deformations, and if the rate of this actuator reaches the maximum rate, there could be a phase difference, which could explain the instability. The concept of body freedom flutter is not new, but the explanation of a physical mechanism that can explain the results obtained is, in the author´s opinion and knowledge.

8. Conclusion

In a previous article (Siqueira, *et al.,* 2024),a more detailed explanation for the flutter mechanism in an aircraft had been proposed. The explanation relied on information on the damping, frequency, amplitudes and relative phases of the torsional and bending movements of each aeroelastic mode, and in each structural element. The use of these parameters has been known and done for a long time. Many aeroelastic stability analyses depend on knowing the structural modes and the frequency and damping curves along the airspeed. The difference there was in proposing the dissociation of each mode into torsional and bending movements. And in the analysis of each of these movements, as if each were a sub-mode within the structural modes already known.

This article proposes the cause of the sudden phase change in wing bending, presented in the previous article and repeated here.**The novelties here were the concepts of structural actuator, and saturation on it, that can be cause of the sudden variation on the bending phase.This concepts allowed the analogy of two different aircraft phenomena: Flutter and PIO. Based on this analogy, the concept of structural actuator saturation could be proposed as one root cause for the flutter of the airplane analyzed.**

The analyses were carried out using data from just one modeled aircraft. This can be seen as a limitation of the results presented. Nevertheless, the conclusions drawn from the analysis indicate an additional theory that can be used in aeroelasticity analysis. The decomposition of the modes into bending and torsional movements, and the analysis of each one individually, for each structural element, can provide much more information. Based on the eigenvectors, the cause of the instability can be found, even before the flutter occurs. Here, the cause was the change in phase of the bending movement. And the cause of this phase difference **may have been the saturation of the structural actuator.** It's still a hypothesis that needs to be confirmed. Knowing and confirming this cause may allow to develop ways of avoiding this saturation, and consequently avoiding the phase change in bending, and consequently delaying the flutter speed, and increasing the flight safety of new aircraft. The hypothesis proposed here should be confirmed in the study of other aircraft, with traditional as well as modern configurations, and confirmed with experimental data. The content of this article indicates a new direction in aeroelasticity research. This research can contribute greatly to the development of safer aircraft.It is by no means intended to replace the criteria and form of analysis developed throughout the 20th century, but rather to provide a new tool and way of looking at such analysis.

Acknowledgments

The authors acknowledges the engineer John Jeffery, who proposed the idea of seeing and modeling the wing and tail flexible structures as actuators, in 2011. Idea called here as structural actuator.

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