Flight envelope expansion based on active mitigation of flutter via a V-stack piezoelectric actuator

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Abstract. The instability of the aircraft's flexible control surfaces caused by uncontrolled vibrations represents a challenging issue of the aviation security. Flutter is a violent vibration whose amplitude grows strongly in a short time. Once the flutter is reached, the plane is destabilized and it can no longer be controlled. This paper proposes a specially designed demonstrator intended to extend the flight envelope by raising the speed limit at which the flutter occurs. The anti-flutter demonstrator is an intelligent airplane wing model made from a longeron covered by an aerodynamic layer. The wing has an aileron as a primary flight control surface, at one end, and a flange conceived to fix the wing in the aerodynamic tunnel, at the other end. The actuator consists in two V-shaped piezo stacks. The main advantage of the piezo actuator, the bandwidth (about 30 Hz), is exploited. The aero-elastic control is efficient if the deflection of the control surface is of a few degrees while the frequency is of at least 25-30 Hz. The control law is obtained through the receptance method of eigenvalues assignment using the on line input/output measured transfer function rather than the knowledge of system matrices.

1. Introduction
The primary flight surfaces of the airplane are flexible surfaces, subject to aeroelastic forces. The interaction between inertial, elastic and aerodynamic forces can trigger a disastrous aeroelastic dynamic phenomenon called flutter. The flutter is a self-sustaining unstable oscillation that increases quickly in intensity. It is a complex and difficult process to study. In the case of planes, as speed increases, there is a threshold beyond which structural vibrations can no longer be damped, and they begin to increase in amplitude by accumulating energy in the structure.

At the dawn of aviation, there were several flight disasters caused by unstable vibrations [1], [2]. Gradually, flight flutter tests were introduced [1], [3]. At present, all aircraft get their approval to fly after passing a series of tests, including a test for establishing the flight envelope, in which a safety margin is considered. However, no flight regime is really immune to flutter [1]. To counteract this phenomenon, passive methods such as mass balancing, increased rigidity of the structure and change of geometry were initially used. Unfortunately, these methods led to an increase in the total weight and lowered the aircraft’s performance. Recently, active flutter control methods have been implemented using the actuators of the aircraft primary flight controls [4]-[9].
As flight flutter tests are expensive and time consuming, often leading to irreversible destruction of the aircraft, complementary methods are considered: mathematical modelling accompanied by numerical simulations, optimization of control laws implemented on primary flight controls, reconsideration and design of better aerodynamic structures, ground tests and wind tunnel tests. A comparison between theoretical methods and numerical simulations during flight is presented in [10].

The present paper rolls out a wind tunnel tested demonstrator for the active control of the structural vibrations of a wing model with aileron and piezoelectric actuator.

2. Physical model description

The anti-flutter demonstrator is an intelligent airplane wing model made from a longeron covered by an aerodynamic layer (profile NACA 0012). The wing has an aileron as a primary flight control surface, at one end, and a flange conceived to fix the wing in the subsonic tunnel, at the other end. The spar is a 1 mm thick rectangular tube (1200x120x25 mm) provided with notches to control its stiffness. The elements defining the aerodynamic surface are made from wood or ROHACELL 71S resin. The wing structure is depicted in Fig. 1.

![Fig. 1. CATIA model of the longeron (left) and wing (right)](image)

The actuator is made up of two V-shaped piezo stacks. The advantages of the piezo actuators are the reduced size, the wide bandwidth and, last but not least, the high energy density. There is a disadvantage related to their reduced stroke, but the kinematic scheme of Fig. 2 shows how to achieve a multiplication of the output stroke, at the point P5, with the price of a force demultiplication. The piezo stacks are arranged along the segments P1P3 and P2P4. When the stack P1P3 is activated by increasing the supply...
voltage $V$, $V_0 + \Delta V(t-\tau)$, which determines its extension to move to the right and slightly below the articulated point $P_3$, the stack $P_2P_4$ is supplied with the voltage $V_{02} - \Delta V(t)$

$$\Delta V(t - \tau) = \begin{cases} 0, & t \leq \tau \\ \Delta V, & t > \tau \end{cases}$$

which causes the withdrawal to the left and slightly downward of the articulated point $P_4$ therefore not to withstand to downward movement of the articulated point $P_5$ in the slider crank mechanism. This provides the movement with positive angle (up) $\delta$ of the aileron. The two stacks are successively active versus passive, in the sense of the presented description. The constant $\tau$ defines a delay in the application of voltage to “active” stack, to ensure the withdrawal of the passive stack. The left side of the scheme is actually in a different parallel plane to the right side, the one in which the aileron and the slider crank mechanism, sketched in the point $P_6$, are represented. The mathematical model of the actuator and the numerical simulations are found in paper [11]. The deflection of the control surface must be at least 5-6 degrees, with the frequency band of at least 25-30 Hz, as specified in work [12]. A particular attention is paid to the bandwidth and this clause is clearly in favour of piezo actuators. Obviously, the classical actuators do not have resources for this high bandwidth value; but even for piezoelectric actuators, stroke requirements may be problematic. The piezo stacks NAC2022-H98-A01 were bought from NOLIAC and have the following basic properties: height 98 mm, stroke 148.8 μm, capacitance 19010 nF, maximal force developed 4200 N, maximum operating temperature 150°C, material NCE51F.

Fig. 3: Frequency characteristics of the piezoelectric actuator

3. Preliminary results of benchmark tests in the Mechatronic Lab
Various tests were carried out to determine the frequency characteristics of the piezoelectric actuator without load (white line), with aileron as inertial load (red line) and with equivalent mass (blue line), see Fig. 3. The actuator without inertial load has strong resonances at frequencies of several hundred Hz. In the case of the actuator with mounted aileron, the bandwidth decreases to 15 Hz with an unacceptable resonance peak at about 12 Hz. Green curves are made with PID control with various coefficients experimentally determined. On the right side, the system is more dynamic (e.g. with increased bandwidth), and has an acceptable resonance peak of 2 dB. With a suitable choice of parameters for the PID controller, a suitable bandwidth of at least 30 Hz can be provided.
The model was designed to create a realistic, elastic wing, unlike most rigid models with external springs simulating elasticity as found in literature [13]. A second criterion was to ensure the occurrence of flutter for the uncontrolled system under the conditions of the INCAS subsonic wind tunnel. Measurements of vibration modes were performed in the Mechatronic Lab using the experimental assembly shown in Fig. 4. Table 1 compares the calculated and the measured values.

| mode | CATIA frequency [Hz] | measured frequency [Hz] |
|------|----------------------|-------------------------|
| 1    | 6.23                 | 5.93 bending            |
| 2    | 10.21                | 11.70 torsion           |
| 3    | 20.83                | 22.73 bending           |
| 4    | 26.32                |                         |
| 5    | 29.83                |                         |

The wing with aileron and piezoelectric actuator was mounted in a vertical position in the subsonic wind tunnel to determine the air velocity at the time of the flutter. The air velocity gradually increased to verify the moment when the flutter occurs. The experiment led to the following results: flutter velocity - 41 m/s, flutter frequency - 5.8 Hz. As it was expected, the wing structure, specifically the longeron, suffered major damages during the flutter (Fig. 5), therefore a new specimen had to be manufactured. The designer of the new specimen had to provide a wing with a lighter aileron meeting the requirements of the first two frequencies estimated by CATIA package (6.23 and 10.21 Hz) and measured (5.93 Hz and 11.7 Hz).

4. Wind tunnel tests and results

Based on the experimentally obtained frequency response, the transfer functions for the pole allocation were determined. This operation was required by the receptance method for the synthesis of the control law [14]. The bandwidth is consistent in the context of a 5.8 Hz measured flutter frequency.

The new wing has been tested to increase the flight envelope based on active vibration control. Initially, a roots locus in the open loop was made at successive air velocity of 0 m/s, 5 m/s, 10 m/s, ..., 25 m/s, based on the identification of the transfer functions from the actuator to the two accelerometers. With the uncontrolled system, the evolution towards the instability of a mode was followed by noting the velocity of the air flow which is responsible for the occurrence of the unstable poles (Fig. 6). The next step was to repeat the tests, this time in a closed loop observing, as it was expected, the widening of the aeroservoelastic stability range, namely increasing the aeroelastic stability limit relative to the airflow velocity, Figs 7-9.
5. Discussion and conclusions

The experimental results of the tests performed on the wing model and the piezoelectric actuator indicate 1) the piezo actuator’s compatibility with the flutter control objectives and 2) the efficiency of the receptance method in the synthesis of the control law. Such an objective would have been more difficult to achieve with a hydraulic or electric actuator, given their low cut-off frequencies. The receptance method has proven to be consistent: the input-output transfer functions have been identified with good accuracy, allowing to determine the amplification factors for position and speed reactions and, consequently, a consistent attenuation of approx. 8 dB of the resonance vibration (Fig. 9).

Fig. 5. Left and middle: sequences of flutter evolution of the wing at 41 m/s air speed; right: wing system with actuator during complex tests to validate the method of increasing the speed of the flutter; at the top of the wing is the piezoelectric actuator. At the top right are the two accelerometers.

Fig. 6 The location of basic bending and torsional poles in open and closed circuits, depending on the air velocity. Only poles with positively imaginary side are represented.
Fig. 6 is instructive in terms of the evolution of poles of open and closed loop transfer functions, as well as the air velocity. One may notice that poles move away from the real axis (based on a more pronounced damping) as air velocity increases, an effect that is blunted in the absence of control, but amplified in its presence. The speeds represented in figure (10, 15, 20, 25, 30 m/s) are outside the speed of the flutter. Near the speed of the flutter, the data from the literature show that for the torsion mode there is a precipitated turn of the poles towards the imaginary axis [15].

![Fig. 6](image1.png)

The pole allocation strategy was the following: a) the transfer functions are identified at a certain air velocity; b) the control law based on the allocation of poles for one mode or two basic modes is determined; c) the poles prescribed for allocation to the closed loop system are chosen to double the bending mode damping factor and increase the torsion mode’s own frequency by 2 Hz, in the idea of increasing the spread of the two modes, since, in flutter, the two modes will overlap. The idea of increasing the spread is translatable in terms of “robustness” of the control law.

Here are a few words about active control technology based on the receptance method. It actually has the data of an emerging technology. A comprehensive analysis of the concept could be found in [16]: the attributes would be (i) radical novelty, (ii) relatively fast growth, (iii) coherence, (iv) prominent impact, and (v) uncertainty and ambiguity! From the perspective of the attribute (v) an emerging technology is still regarded with scepticism by the control engineers.

![Fig. 7](image2.png)

![Fig. 8](image3.png)
Basically, the receptance method only requires on-line measurements of the frequency response of the structure, eluding the need to know the $M$, $C$, $K$ (mass, damping and rigidity) and $B$ (control influence) matrices. In the receptance method, neither the model order reduction nor the synthesis of an estimator for unmeasured state is required. In principle, this controller can be continuously corrected on the basis of the measurements, with beneficial consequences in the performance of feedback. These attributes provide the method with a rapid growth in applications, once gained the confidence of those interested. The method is derived from a matrix analysis result, the Sherman-Morrison formula [13], which gives the inverse of a matrix in case of a change in rank, depending on the inverse of the original matrix.

Fig. 9. The response of the system to resonant excitation applied for 5 seconds: amplitude of 2 degrees and frequency equal to its own bending mode frequency of 5.8 Hz. Left: open loop; right: closed loop, the control is introduced at time $t = 5$ sec.

In conclusion, the most significant result of the paper is the advanced testing in the wind tunnel of a powerful method of control synthesis, the method of receptance, having a pronounced character of novelty (the latest data on the net refer to a PhD thesis from 2015 [17], from Louisiana State University, a theoretical and not experimental work).

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