Article

Optimization of the High Aspect Ratio Wing with Position and Distribution of Aileron Mass on the Speed and Frequency

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Abstract: As the aileron mass parameter and its position on the velocity and frequency of the flutter is an important problem in design of the aircraft wings, the optimization of the composite wing with an aileron is represented in this paper. Mass properties and its distribution have a great influence on the multi-disciplinary optimization procedure based on speed and frequency of flutter. At first, flutter speed was obtained with and without aileron, then aileron was mass-equilibrated and other studies were performed using the proposed method. It is deduced that changing the position and mass properties of the aileron the speed and frequency of the flutter changed. The position of the aileron was determined for better wing performance in flutter instability and minimizing the composite stress. In the present study, it has been attempted to model the aerodynamics of the problem under ultrasound with the panel method, and the structure has been modeled using finite element method and coupled with the aerodynamics. Using the p-k method, the equations are solved and the results are extracted.

Keywords: Flutter Speed; Flutter Frequency; Composite Wing; Aileron, multi-disciplinary optimization method

1. Introduction

Due to the structural interaction of the Arial vehicle with the air in which it is flying, at a certain speed, its self-vibrations occur, which is called fluttering. Flutter is a destructive phenomenon that in categories is referred to as the self-vibrational phenomenon that occurs for flying objects. This phenomenon will lead to aggravation and high-amplitude vibrations [1–3] in the absence of sufficient damping in the system, which will also lead to structural failure[4]. Indeed, The investigation on flutter of aero structures was firstly conducted in 1916 [5] on a bomber in Lancaster, England. The mechanism included a coupling of the body's twisting modes and the Elevators' rotating, asymmetrical mode. The elevators operated independently in this aircraft, and to solve this problem, the elevators were connected to each other and worked together at the same time [6]. Wing flutter's levels by control surfaces became apparent during World War I, and aileron one became widespread during this time .Von Baumhauer and Koning [7] suggested using a balancing weight around the hinges of the control surfaces as a means of preventing flatulence. However, after that, several low-risk flutter examples of control levels emerged.

There is also the phenomenon of the effectiveness and reversal of the functioning of the control surfaces, but they are not as catastrophic as the aileron[8]. The studies on aileron effectiveness in subsonic regime as an active control surface to decreases undesirable loading was conducted by Jacobs [9].Later, using the experimental results of the scaled wing in the wind tunnel, compared the aero elastic with numerical analysis[8,10].

During studying flutter, scientists and engineers [11–13] were able to analyze flutter behavior by stating computational theories and tools [14]. In the 1920s and 1930s, non-permanent aerodynamic theory was introduced [15]. Thirty years later, strip aerodynamic theory, beam structural model, non-permanent lifting surface methods, and developed analysis of finite element models were examined [16]. With the advent of digital computers, other powerful methods have been developed that include aerodynamic theories [17,18] and structural modeling with numerical method [19–21], control theory (specific to aeroelasticity), and structural dynamics [22]. Indeed, the distribution of mass and stiffness in the structure has a direct effect on the speed and frequency of the flutter [23,24]. The presence of any structural component that has a significant mass and stiffness relative to the mass and stiffness of the main structure can affect the speed and frequency of the flutter. These include a tank, weapon, landing gear, and control surfaces such as aileron.

The effect of the control surfaces on wing performances is considered as the one of the challenging problem in designing procedure of the airplane structures. Study on positioning and instability problems of the control surfaces[25] at the trailing edge of a wing was conducted by researchers via Finite volume method [26–28]. Indeed, Dixon and Mei expanded the use of applicable method for composite panels as the common materials in Arial vehicle industry. Von-Karman strain-shifting relationships were used to show large deviations and aerodynamic loads following the first-order quasi-stable theory. They solved the equations of motion using linear optimized modes.

The finite element method (FEM) as another useful approaches was founded and developed for flutter boundary analysis, finite oscillation, and thermal problems [29–31]. Shi [32] represent the gust loads FEM form formulation to study the wing instability behavior. Based on the model, the other studies were conducted to assess flutter clearance of the wing with the control surfaces [33].

Among the optimization methods [34,35], the multidisciplinary design optimization (MDO) approaches play important role in design of the aero structural vehicles under static and dynamic criteria [36,37]. Design and estimation of the high aspect ratio composite wings performances under flutter condition and weighting reduction using MDO method is common in new aero-structural components [38,39]. In practice, aerospace structures are subjected to different forces in different parts, which cause stress in the structure. In isotropic structures, it is possible to change the thickness based on the stress vortices by manufacturing methods. In these structures, the thickness change is continuous and thus the structure continuity is maintained. In composite structures, designers divide the structure into different parts based on these stress gradients [37,40], and for each part, in addition to changing the lay-up; they also change the location of the control surfaces appropriately. Thus, thickness reduction is completely depend on the control surface position especially aileron one.

In the present paper, the effect of aileron's position as well as its mass inertial moment on the speed and frequency of the flutter have been studied first. To solve this problem, the finite element method was used in such a way that first the aerodynamic wing model was modeled using panel theory and then the limited component model of the wing structure was created. Then, the problem was solved using the P-K method. Nastran software was used for this purpose. Then, using MDO procedure the best position of the aileron with the minimum state of the TSAI–WU stress via USAR [41] and JAR25 [42] criteria's is opposed.

2. Problem design

Depending on the dimensions and weight of the aircraft, the defined maneuvers for it, whether permanent or sudden and different weather conditions, different forces are applied to it with small and large scales and the wing structure must be able to meet all different conditions with a suitable reliability factor to satisfy and provide a safe and secure flight. Therefore, the design of the structure of an aircraft, especially its wing with control surface like aileron, should be done in such a way that, in addition to it has the minimum possible weight and stress criteria defined in the air regulations; it should be pass the flutter criterion.

Here, The represented wing structure is an all-composite carbon / epoxy wing with a high aspect ratio and laying s[45, -45,45,0,90] that consider as our design problem. The total mass of the wing with the aileron is about 247 kg. The mass of ailerons is about 5 kg. The wing structure has 3 spars and 15 ribs. Figure (1) shows the overall dimensions of the wings.

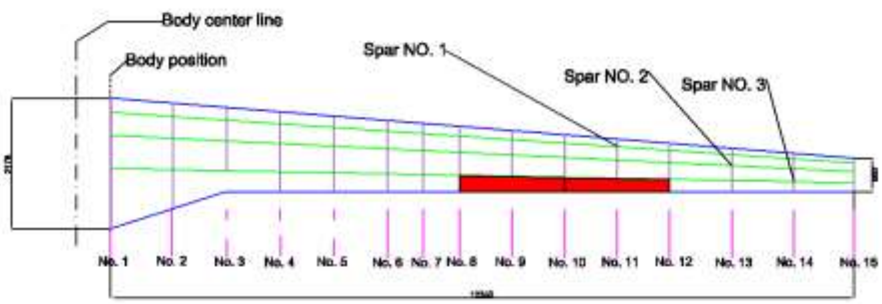

Figure 1. General dimensions of wing and position of aileron reference (eaten as a hash)

The finite element model of aerodynamics and wing structure is presented in Figures (2) and (3), respectively.

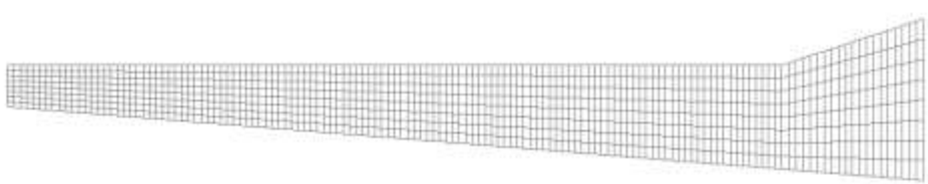

Figure 2. Aerodynamic wing meshing based on DLM method.

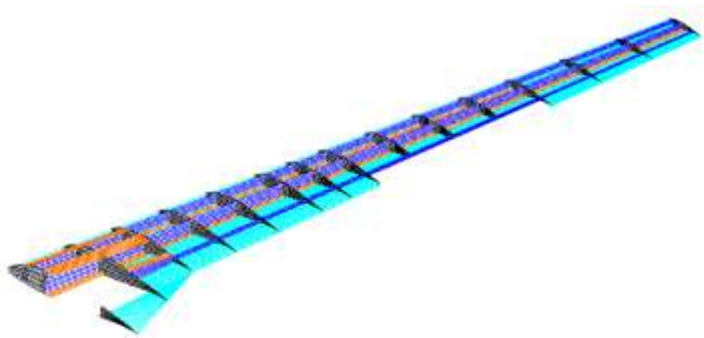

Figure3. Frame structural mesh.

The boundary conditions for solving this problem, considering that the wing is completely attached to the body, are completely fixed and are numbered one and two from the beginning of the spar.

Table 1. Material Specifications

Parameter	Carbon/ epoxy
t (mm)	0.28
Dens (kg/mm^3)	1.42E-6
Ex (MPa)	44250 0
Ey (MPa)	44250
vxy	0.037
Gxy (MPa)	5000
Fxt (Mpa)	442
Fxc (Mpa)	243
Fyt (Mpa)	442
Fyc (Mpa)	243
Fsxy (Mpa)	45

2.1 Wing loading

To analyze the wing structure of the aircraft, it is necessary that the loads applied to it be available in different flight conditions. In general, depending on the aircraft's flight mission, different loads are applied to the aircraft's surfaces and wings. To ensure that the aircraft structure, including its wing and its facility, is able to withstand the worst loading conditions, the aerodynamic loading group determines the worst loading conditions obtained from the above conditions in the worst flight conditions and by applying the reliability coefficient in the standards. Different structural members are designed and their strengths are determined in accordance with paragraph JAR25-301 [42] for final loads and loads multiplied by a certain reliability coefficient. In this paragraph, the load limit is defined as the maximum load that may be applied to the structure during the service life. Accordingly, in accordance with paragraph USAR-305 (a) [41], the structure must withstand a certain load without permanent deformation, and in accordance with paragraph (USAR-305 (b) the structure must be able to withstand the final load for at least 3 seconds to cause rupture. To apply the reliability coefficient in accordance with USAR-305 clause, the reliability coefficient is 15.1 and in accordance with USAR307 clause, the critical load coefficient is 3.8. It has been used to apply the load on the composite wing with aileron.

2.2 Flutter wing analysis

Here, flutter analysis is conducted by aero elastic section of the Nastran software module. The data required for the flutter analysis is obtained by modal wing analyzing. The flow regime for the above mentioned worst case was selected as the unstable type and the Mach number equal to 0.6 was assigned to the problem. The air density was 1.225 kg / m3. Also, 1 to 300 meters per second was considered for estimating the speed range.

2.3 Effect of aileron on wing flutter

Investigation of the aileron effect on the speed and frequency of the flutter wing as a main parameter of design criteria is represented in this section. The results are presented in Table (2). The results show that the flexural modes 3 and the torsional 6 wings are coupled together and lead to the flutter. Figures 3 and 6 of the wings are presented in Figures (4) and (5), respectively.

Table2. Flutter wing speed and frequency in reference mode

Parameter	With Aileron	Without Aileron
Flutter Speed	210	190
Flutter Frequency	17.4	16.45

The velocity-frequency and velocity-damping diagrams are shown as a sample for the wing, despite aileron in the reference position in Figures (6) and (7) for sea level elevation. As shown in the figure, as the speed increases, the two frequencies of the system approach each other and approach the nearest distance at a speed close to 190 m / s (684 km / h). . This indicates that the flutter phenomenon is occurring at this speed. In aero elastic analysis, basically, according to the masses of mass, damping and generalized stiffness of aero elastic, the system equations in generalized coordinates are expressed as follows:

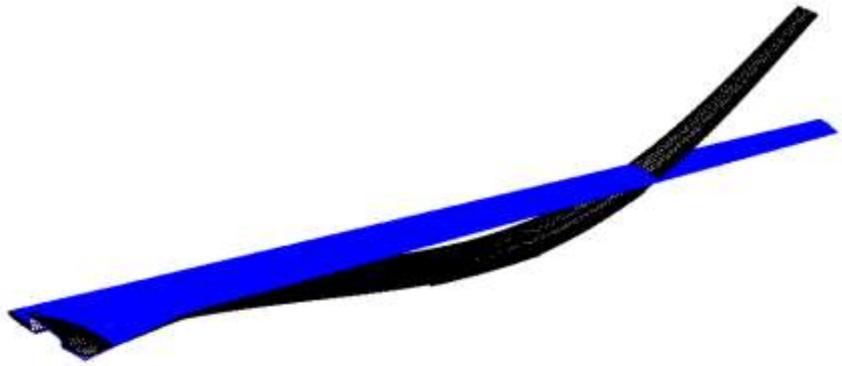

Figure4. Shape of the third wing mode with aileron (bending -1 / 11 Hz)

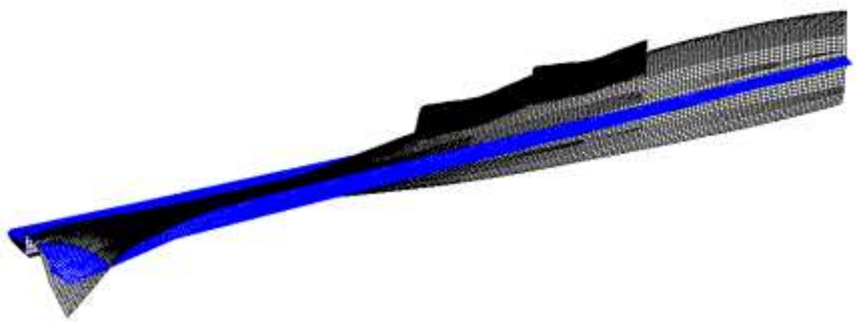

Figure5. The shape of the sixth wing mode with aileron (torsion -1 / 33 Hz)

$$[M]_{Aeroelastic}\{\ddot{q}\}+[C]_{Aeroelastic}\{\dot{q}\}+[K]_{Aeroelastic}\{q\}=0\,. \tag{1}$$

These matrices are constantly changing and updated with the flow rate. Since the matrices mentioned change with the velocity of the flow, the parameter P in the solution process of the equation also changes constantly. The imaginary part of this parameter is called the frequency and the real part is called damping. Given the assumed solution, it is clear that when the damping is positive (ie, the true part P becomes greater than zero); the system's response grows over time and tends to infinity, which is what causes the structure to diverge. Therefore, the point at which the damping changes from negative to positive is called the flutter point. Due to the optimization procedure the structure can be simplified. So, the composite wing is considered as shell element and also the aileron was modeled as a concentrated mass with the main structure of aileron and in the position of aileron's center, and the results were compared. The results are presented in Table (3).

Table 3. Flutter wing speed and frequency in reference mode (comparison of the main model and the centralized mass model of aileron)

Parameter	Original Aileron	Aileron with concentrated Mass	Error percentage %
Flutter Speed (M/sec)	190	190	0
Flutter Frequency (Hz)	16.45	16.15	0.6

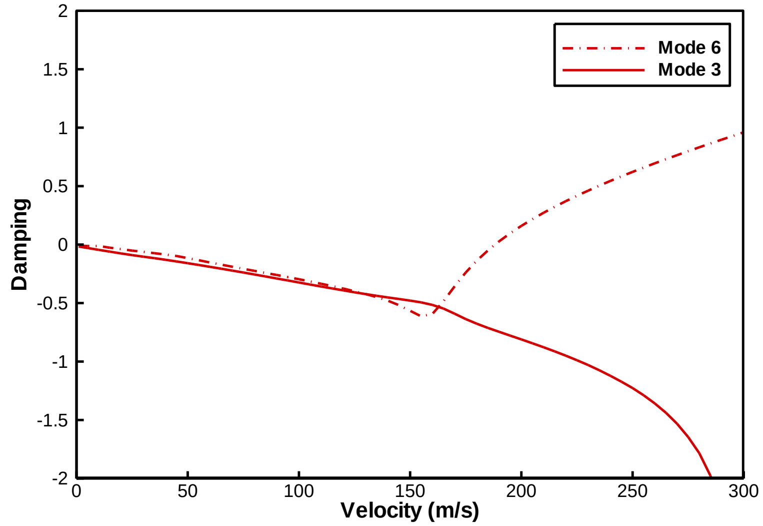

Figure6. Damping versus speed

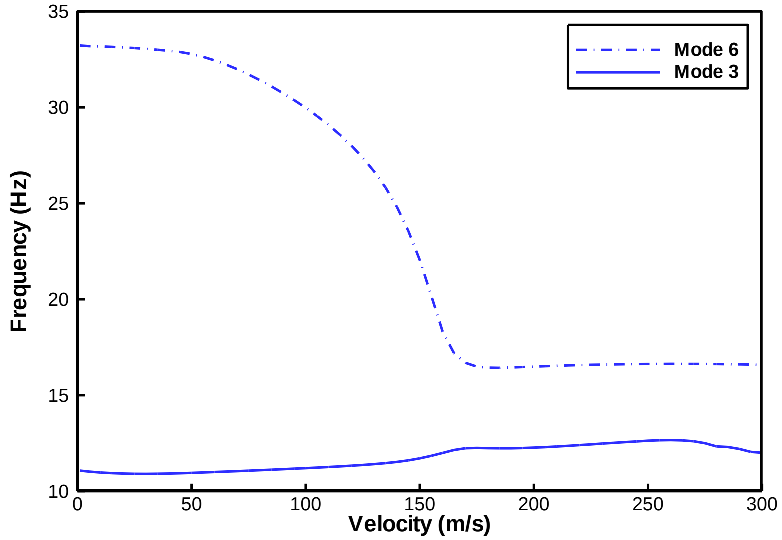

Figure7. Frequency versus speed

Due to the fact that the results of the simplified model are slightly different from the original model, the simplified model was used to continue the research process.

3. Optimization based on the strength and flutter criteria

According to the Genetic Algorithm (GA) and Artificial Neural Network (ANN) a new Multi-disciplinary design optimization (MDO) method is adopted to propose the best position of the aileron on the composite wing to postpone flutter and alleviated the stress of the root. These design flow include parametrization aileron position, optimization algorithm, and a surrogate model on FEM (NASTRAN) software. Design of experiments (DOE) is also employed to create the sufficient database base on the main mentioned composite wing with aileron position along with Neural Network Algorithm. Based on the created data base, the flutter response and TSAI–WU stress criteria of composite wing are evaluated. The new aileron positions are extracted using the numerical calculation. The data base is composed based on the ANN results that converge to numerical results. Finally, using the results of the NASTRAN software, the objective function is examined to assess the target goal satisfaction.

3.1 Optimization procedure

The minimizing stress due to above worst case loadings along with flutter avoidance criteria make the design optimization algorithm .Indeed; the procedure is followed to minimize the stress due to gust loading along with increasing the flutter speed.

$$\mathrm{OF} = \alpha_1 K_{\mathrm{flutter}} + \alpha_2 \sigma_{\mathrm{TSAI-WU}} \quad (2)$$

Where the design variable or weighting coefficient can be introduced as α_n and represent the importance of the each parameter. Also, the K_{flutter}parameter is called the reduced frequency and represented the dimensionless instability parameter for self-excitation of the composite wing, and finally $\sigma_{\mathrm{TSAI-WU}}$is semi-equivalent stress that defined for composite materials based on the USAR and JAR22.

Based on the meta-models idea beside ANN and also through the FEM aero-mechanical calculations of original composite wing, design of the experiments method is taken here. The network is trained via feed forward- back propagation network with 8 hidden layers and one output neuron. Based on the experience, the proper range of the aileron position is set to be in a 5% deviation of original position. The ANN along with the approximated function (Eq. [2]), the design flow is started and by predefined GA, the OF value is approximated and compared with the result of the 3D FEM simulation and then ANN data base is updated (Figure (8)).

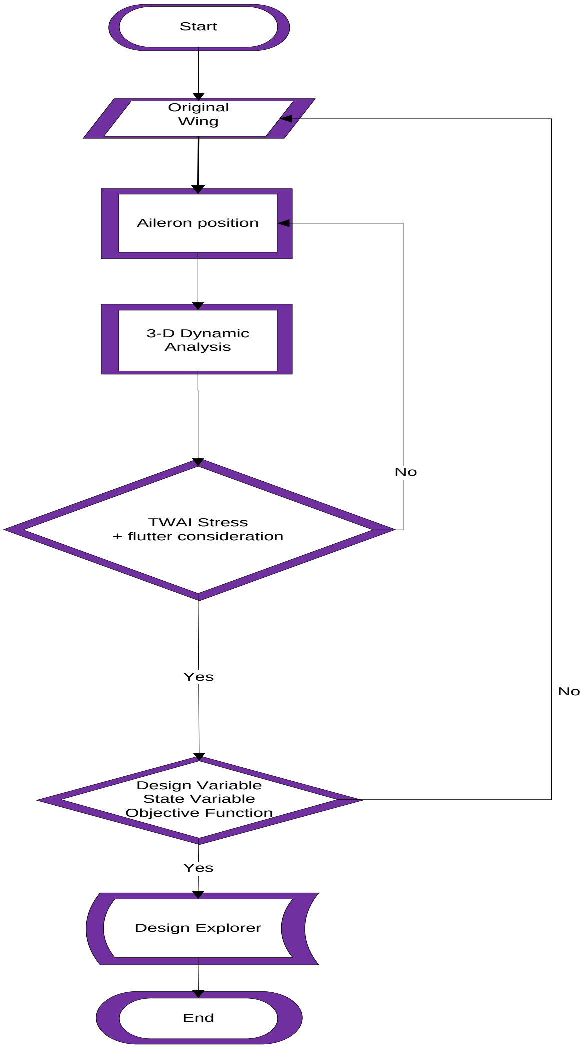

Figure8. MDO Flow Chart

4. Result and Discussion

According to design of the experiment, the composite wing is followed by 50 Latin Hypercube type. 75% of the experiments are employed for network training and the other data are used for network validation. Here, the values of precision for efficiency are considered 99.9% with 0.09 % deviation value. Based on the FEM calculations, the results are compared with approximation of the network in each ANN loop to assess the precision of the network in aileron position prediction. Using 35-generation and 70 members in each generation the process of the optimization is performed. If the precision of three dimensional FEM simulations are less than 0.3% the results of the neural network is applied for following the optimization procedure. The speed and frequency of the flutter of the best predicted position of the aileron are represented in the following Table (4).

Table 4. Flutter wing speed and frequency for different aileron positions.

Number	Aileron position relative to the middle axis of the body (meters)	Flutter speed (meters per second)	Flutter Frequency (Hertz)
1	1.95	215	16.7
2	2.66	195	16.2
3	3.38	Flutter does not occur	-
4	4.55	Flutter does not occur	-
5	5.94	Flutter does not occur	-
6	6.23	177	15.3
7	6.94	193	15.9
8	7.14	182	15.1
9	7.55	123	16.9
10	8.61	Flutter does not occur	-
11	9.22	Flutter does not occur	-

Also the estimated stress results are compared with main composite wing to reach the location of the aileron. The normalized TSAI–WU stress values for the all represented position show 0.45 to 1.2 normalized stress intervals. Figure(9) shows the normalized TSAI–WU stress for the six specified position during the optimization process without flutter happening.

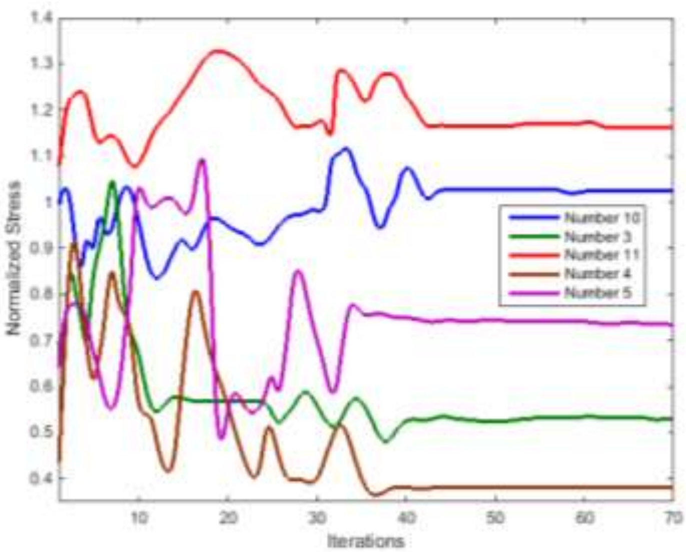

Figure (9). The normalized value of the TSAI–WU criterion during the optimization process

Finally, the multi-disciplinary optimization method represented the number 5 of the above table. Indeed, the procedure represented the aileron position that avoids the flutter happening with the minimum root stress value for the composite wing.

5. Conclusion

In this study, the effect of aileron's position and its critical properties on the composite wing flutter with a high aspect ratio was firstly investigated. Given that the speed and frequency of the flutter are directly related to mass distribution, the effects were so dramatic that in some situations the phenomenon of the flutter did not occur at speeds of up to 300 m / s. This study also showed that concentrated mass can be used instead of aileron's total modeling, and it was shown that in equation there is no need to unify the inertial moment of mass inertia and only the mass and positions of the center of mass are effective. Finally, based on the USAR [41] and JAR25 [42] critical loading definitions along with of the flutter avoidance criteria, the multidisciplinary optimization method was employed and represented the best aileron position of composite wing. Therefore, the aileron position can be selected if possible so that the flutter phenomenon does not occur. The results show the flutter speed avoidance and 50 E5 Pa stress in root of the composite wing.

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