Optimization of composite wing spars for an unmanned aerial vehicle

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Abstract. In this paper, the weight optimizing of an unmanned aerial vehicle wing spar was designed by using composite material. The optimization parameters were considered, respectively: the wing mass, the location of the spars and ribs, and the spars mass. Determined the selecting of wing spars locations for optimizing spars design based on the minimum weight of the wing. Layer optimizing was used to reduce the weight of composite wing spars. The thickness of front spar and rear spar element such as web and flange were optimized by criterion of allowable normal stress and deflection. The analysis of stress-strain state for all variants were carried out in the FEMAP software package. As the result of analysis, the total weights of composite wing spars reduced 18.17% than the original spars.

1. Introduction
Currently, unmanned aerial vehicles (UAV) are widely used in military and civil areas, for conducting surveillance, reconnaissance, patrol and other purposes. These aircraft are characterized by a low speed and a long endurance in the air. The reducing weight of structure is the important role in designing of UAV structure for maximum payload. One of the most effective ways to reduce the weight of the unmanned aerial vehicles wing spar is the use of composite materials [1,2]. In this paper the wing of UAV was considered as two-spar type. The selection of optimal spars position was the main stage of designing a UAV wing. Determine the optimal spars locations of a composite wing spars according to minimum mass under aerodynamic pressure load. Optimal I-section wing spar location and design was considered by the finite element method using FEMAP software. The spar is the main longitudinal element of the wing, which receives the load. It perceives part of the bending moment and the transverse shear force of the wing [3].

According to the optimal spar locations, the front spar and rear spar design are created. In layer optimization process, we were divided by three section in each spar and analysed the thickness of spars base on allowable stress and deflection. The objective of this paper was to determine the optimal composite wing spar location and to design a front spar and rear spar with the minimum weight

2. Methodology and material property
The object of the study was a straight wing of the UAV type "Hermes 450" with a span of 10.5 m, unsymmetric profile NACA 4412 and the chord length was 0.78 m (figure 1) [4]. The spar flange and
web are modeled by a shell element (laminate). The material direction for longitudinal load bearing elements is directed along the axis Z and for transverse elements is along the X axis. The finite element model is prepared by meshing, contact nodes elements and constraining the model by applying material properties and boundary conditions in FEMAP software package. Unidirectional carbon fiber (T300/epoxy) was considered for all load bearing elements of the wing (table 1). The lay-up structure of unidirectional carbon fiber for all load bearing elements of the wing was chosen as the same: (0°) [5].

![Figure 1. Half of UAV wing model](image)

### Table 1. Physical–mechanical properties of unidirectional carbon fiber (T300/epoxy)

| Properties                          | Value | Unit       |
|-------------------------------------|-------|------------|
| Longitudinal modulus, $E_1$         | 181   | GPa        |
| Transverse modulus, $E_2$           | 10.3  | GPa        |
| Shear modulus, $G_{12}$             | 7.17  | GPa        |
| Longitudinal tensile strength, $\sigma_{1+}$ | 1500  | MPa        |
| Longitudinal compressive strength, $\sigma_{1-}$ | 1500  | MPa        |
| Transverse tensile strength, $\sigma_{2+}$ | 40    | MPa        |
| Transverse compressive strength, $\sigma_{2-}$ | 246   | MPa        |
| Shear strength, $\tau_{12}$         | 68    | MPa        |
| Density, $\rho$                     | 1600  | Kg/m³      |
| Thickness layer, $\delta$           | 0.2   | mm         |
| Poisson’s ratio, $\nu_{12}$         | 0.28  |            |

3. **Modeling and calculation for selection of spar location**

In this analysis, the aerodynamic load acting on the wing was determined by using the following equations: [6,7].

\[
P = \frac{Y}{\cos \theta^\prime} \quad (1)
\]

\[
P = Y = G_0 f \quad (2)
\]

\[
P = \frac{G_0 n^a f}{S_w} \quad (3)
\]

Where, $P$ = pressure load acting on wing, $Y$ = lift force, $\theta = \text{angle between lift and drag force}$, $G_0 = 450 \text{ kg}$, maximum take-off weight, $n^a = 4$, load factor, $f = 1.5$, safety factor, $S_w = 8.2 \text{ m}^2$, wing area. In this paper we were assumed that $\cos \theta = 1$.

The variable parameters for determining the position of the spars and ribs of all cases were shown in table 2. The results of calculations of the wing mass and deflection for the considered variants were presented in table 3. As the results, the optimal variant of the UAV wing based on the minimum weight was defined by the variant 5, in which the front spar was located at 30% of the chord from the wing tip while the rear spar was fixed at 60% of the chord in figure 2.
### Table 2. Optimization parameters of spar position

| No. | Positions of spars (% chord) | Distance of rib (mm) |
|-----|-----------------------------|----------------------|
| 1   | 20/60                       | 400                  |
| 2   | 300                         |                      |
| 3   | 20/70                       | 400                  |
| 4   | 300                         |                      |
| 5   | 30/60                       | 400                  |
| 6   | 300                         |                      |
| 7   | 30/70                       | 400                  |
| 8   | 300                         |                      |
| 9   | 25/60                       | 400                  |
| 10  | 300                         |                      |
| 11  | 25/70                       | 400                  |
| 12  | 300                         |                      |

### Table 3. Results of spars positions

| No. | Mass (kg) | Deflection (mm) |
|-----|-----------|-----------------|
| 1   | 30.3      | 420.9           |
| 2   | 30.3      | 421.0           |
| 3   | 32.8      | 420.3           |
| 4   | 33.5      | 420.3           |
| 5   | 28.4      | 420.5           |
| 6   | 28.7      | 420.4           |
| 7   | 29.8      | 419.6           |
| 8   | 30.1      | 419.4           |
| 9   | 29.3      | 420.8           |
| 10  | 29.5      | 419.7           |
| 11  | 29.0      | 420.8           |
| 12  | 29.3      | 420.8           |

### Figure 2. Comparison of optimal spar location by mass.

#### 4. Determination of aerodynamic loads acting on front spar and rear spar

The design calculation was assumed that the shear force acting only on the spars. Load on front spar were acting along on curve between ribs position. The first load at the end of spar and second load acting at 50 mm from fixed end and the other loads are acting at equal distance of 400 mm. The result of load acting on front spar and rear spar were calculated by the following equations:

\[
q_a = \frac{G_a \cdot n_{\text{max}} \cdot f \cdot b(z)}{S_w}, \quad (4)
\]

\[
q_w = \frac{G_w \cdot n_{\text{max}} \cdot f \cdot b(z)}{S_w}, \quad (5)
\]

\[
q_f = \frac{G_f \cdot n_{\text{max}} \cdot f \cdot b(z)}{S_w}, \quad (6)
\]

\[
q_x = q_a - q_w - q_m \quad (7)
\]

Where, \(q_a\) = total aerodynamic load, \(q_w\) = mass load of the wing structure, \(b(z)\) is, the wing chord in this section. In this paper, we consider a rectangular wing since \(b(z)\) are the same. \(q_x\) – total load on the wing. Fuel was not placed in the wing and, therefore, \(q_m = 0\). In the analysis of load acting on the wing, 60% of the shear force were distributed to the front spar and for the rear spar - 40%.
\[ Q_\Sigma = \int q_z \, dz \]  
\[ Q_1 = 60\% \cdot Q_\Sigma \cdot \left( \frac{H_1^2}{H_1^2 + H_2^2} \right) \]  
\[ Q_2 = 40\% \cdot Q_\Sigma \cdot \left( \frac{H_2^2}{H_1^2 + H_2^2} \right) \]  

Where, \( Q_\Sigma \) – total shear force, \( Q_1, Q_2 \) – shear force for front and rear spar, \( H_1, H_2 \) – high of spar wall.

The results of normal stress and deformation of original front spar (figure 5) and rear spar (figure 6) were shown in table 4.

5. **Modeling of front spar and rear spar**

By thickness optimization, for original front spar, the thickness of upper flange and web are 6 mm, lower flange was 8 mm. For original rear spar, the thickness of upper flange web was 2 mm and for the lower flange - 4 mm in figure 4(a). First section was placed at 2050 mm from the fixed end and the second section was fixed at the distance of 3650 mm while the last section was 5250 mm as shown in figure 4(b). The results of normal stress and deformation of original front spar (figure 5) and rear spar (figure 6) were shown in table 4.
Figure 5. Stress and deflection of original font spar

Figure 6. Stress and deflection of original rear spar

Table 4. Results of original spars design.

| Parts      | Mass (kg) | Deformation (mm) | Stress (MN/mm²) |
|------------|-----------|------------------|-----------------|
| Original spar design | Front spar | 11.79            | 418.3           | 925.1 |
|             | Rear spar  | 5.54             | 410.7           | 671.5 |

In new design model, the result of ply 1 normal stress and deflection of new front spar (figure 7) and rear spar (figure 8) as shown in table 5. The main objective of present work was to reduce the mass of spar. The new design of spars mass were no much change of stress and deflection under the same load. The comparison of original spars mass and new spars mass were shown in table 6.

Figure 7. Stress and deflection of new font spar

Figure 8. Stress and deflection of new rear spar
Figure 8. Stress and deflection of new rear spar

Table 5. Results of new spars design

| Parts       | Mass (kg) | Deflection (mm) | Stress (MN/mm²) |
|-------------|-----------|-----------------|-----------------|
| New spar design |           |                 |                 |
| Front spar  | 9.84      | 428.9           | 925.1           |
| Rear spar   | 4.34      | 432.9           | 671.6           |

Table 6. Comparison of original and new spars mass

| Parts   | Original spar mass (kg) | New spar mass (kg) | Mass reduction (%) |
|---------|-------------------------|--------------------|--------------------|
| Front   | 11.79                   | 9.84               | 18.03              |
| Rear    | 5.54                    | 4.34               | 21.66              |
| Total   | 17.33                   | 14.18              | 18.17              |

6. Conclusion

In this paper, the weight of spars reduced through layer optimization process. As a result of analysis, the location of spars and ribs determined by the criterion of minimum mass based on a given value of the maximum deflection. By thickness optimization of composite layer, the total mass of new design of front spar and rear spar reduced 18.17% of mass of the initial front spar and rear spar.

References

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