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Rib Spacing Optimization of a Generic UAV Wing to Increase the Aeroelastic Endurance

Tolga Vergün[1*] and Ceyhun Tola[1+]

[1]*Department of Aeronautical Engineering, University of Turkish Aeronautical Association, Ankara, Turkey*
[*]*Corresponding author: ctola@thk.edu.tr*
[+]*Speaker: ctola@thk.edu.tr*
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Abstract – Within the content of this research, it is aimed to optimize rib spacing of a generic UAV wing to maximize its flutter speed. Therefore, magnitude of the wing's torsional frequency value and ratio of the torsional frequency to the first body bending frequency value are aimed to be maximized. To perform the optimization process, a parametric wing model is constructed via an in-house Python script. This script draws wing structure, defines material properties, assigns sections, constructs wing assembly, defines interactions, defines boundary conditions, prepares mesh structure and finally performs modal analysis in Abaqus finite element commercial software environment sequentially. Optimization process is accomplished by Mode Frontier optimization software. During the process Multi Objective Genetic Algorithm-2 solver is used. Finally, the optimum rib spacing value is determined for the wing structure.

Keywords – *Wing, Rib Spacing, Optimization, Flutter, Modal Analysis, Abaqus, ModeFrontier*

I. INTRODUCTION

Design and usage of Unmanned Aerial Vehicles (UAVs) especially for military purposes has been rapidly increasing in recent years due to their capability to endure long flight durations without needing a crew and due to their low cost compared with the conventional military aircrafts. In order to increase range and flight time endurance of a UAV, wing area has to be increased while wing weight has to be decreased. Figure 1 represents some of the military UAVs produced by different companies working for Turkish defense industry.

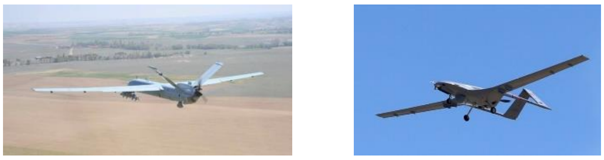

Anka (Produced by TAI) TB2 (Produced by Baykar)

Fig. 1 Some Turkish military UAVs

During the UAV design process weight of the sub-structures (such as: wing, fuselage, tail) is quite critical. Any weight increment in those sub-structures leads to fuel or payload decrement and this may shorten the flight duration of the vehicle. On the other hand, the mentioned sub-structures must have a minimum strength and stiffness in order to accomplish the operation without any structural problem. Therefore, dimensions, thicknesses and locations of the inner structural elements of the wings, fuselages or tails should be carefully designed in order not to cause neither unnecessary weight nor a structural failure.

One of the well-known dynamic structural problem that a wing may encounter during the flight is flutter. Dynamic instability of a flight vehicle or a lifting surface associated with the interaction of aerodynamic, elastic and inertial forces may leads to flutter phenomena [1].

Different optimization studies are conducted so far in order to maximize the flutter speed of a wing. Guo et al. performed a multi-objective optimization process on a composite wing [2]. At the end of the work, they have a weight saving higher than 30% [2]. Zhiqiang, et al. developed and applied a two-level aeroelastic optimization process to optimize a wing structure [3]. As a result of this process, approximately 11% of the initial wing weight is saved [3]. Hasan, performed a multi-disciplinary design and optimization of a composite wing box within the content of his Ph.D. thesis [4]. Samples related to this field from the literature can be increased. According to the literature, flutter speed of the wing is not only depending on magnitudes of the first body bending and torsional frequency values but also depending on ratio of the torsional frequency to the first body bending frequency (frequency ratio). Tola and Nikbay showed in [5] that the flutter speed of a structure can be increased by increasing the torsional frequency and the frequency ratio since this process leads to stiffness increment. Thus, it may be possible to shift the flutter speed of a wing to higher values without changing its weight by only optimizing rib spacing of it.

Within the content of this work, optimum rib spacing value of a generic UAV is determined according to modal analysis results that are conducted in Abaqus environment. During the optimization process, magnitude of the torsional frequency and frequency ratio values are aimed to maximize just changing the rib spacing parameter.

II. FINITE ELEMENT MODEL

A generic UAV wing is constructed and aimed to be optimized for this research. Geometry, material properties, assembly, interactions, boundary conditions and mesh properties are summarized within the content of this topic.

A. Geometry

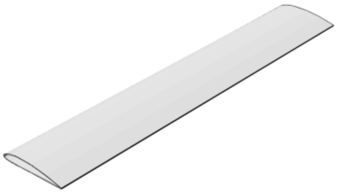
Wing assembly consists of a rectangular main spar, a circular rear spar, a shell wing surface and 11 wing ribs. Those structures are called wing elements and the wing elements used in this work are illustrated in Figure 2.

Rib having gaps

Wing tip rib

Main spar

Rear spar



Wing skin

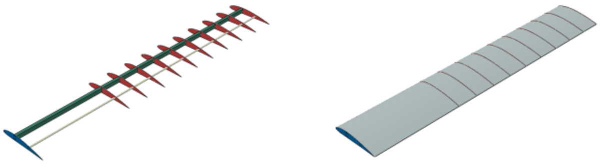
Fig. 2 Wing elements

Dimensions and properties of the wing are summarized in Table 1.

Table 1. Dimensions and properties of the wing

Airfoil	NACA 4412
Wing Span	4 m
Chord Length	75 cm
Rib Thickness	2 mm
Skin Thickness	5 mm
Main Spar Outer Dimensions	40 x 55 mm
Wall Thickness of the Main Spar	2 mm
Rear Spar Outer Radius	12 mm
Wall Thickness of the Rear Spar	2 mm

Assembly of a sample design having 350 mm equal rib spacing can be seen from Figure 3.



Inner Assembly

Outer Assembly

Fig. 3 Sample wing design having 350 mm equal rib spacing

In Figure 3, blue rib corresponds to wing tip. The equal spacing between the red ribs are aimed to be optimized in this work.

B. Material Properties

Whole wing assembly is assumed to be produced from Al-2024 T351 material. Mechanical properties of the material are summarized in Table 2.

Table 2. Mechanical properties of Al 2024 T351 [6]

Property	**Value**
Modulus of Elasticity (E)	73.1 GPa
Poisson's Ratio (υ)	0.33
Density (ρ)	2780 kg/m^3

C. Boundary Conditions and Interactions

The wing is fixed from its root by applying encastre boundary condition and this is illustrated in Figure 4.

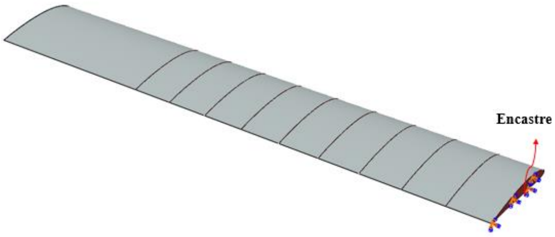
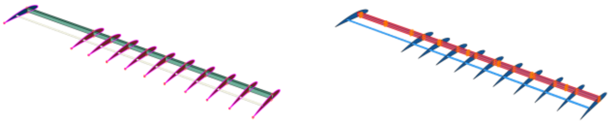


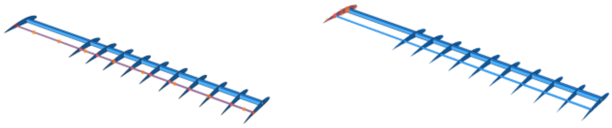
Fig. 4 Boundary conditions

After the assembly process, following interactions are defined: Ribs and wings; main rectangular spar and ribs; rear circular spar and ribs; the rib located at the tip of the wing and spars are glued to each other. Those interactions are illustrated in Figure 5.



Interaction between ribs and wing surface

Interaction between main spar and ribs



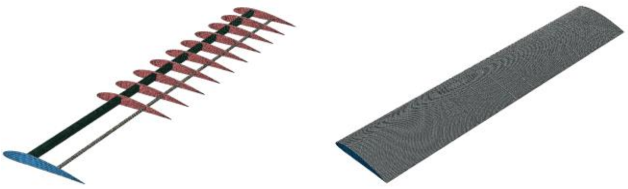
Interaction between rear spar and ribs

Interaction between wing tip rib and spars

Fig. 5 Interactions among the wing elements

D. Mesh

Finite element model consists of 75455 shell elements and 217882 nodes. Mesh structure of the sample wing model can be seen from Figure 6.



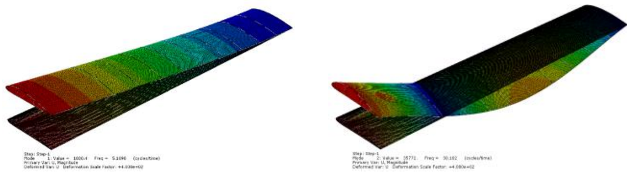
Inner mesh

Outer mesh

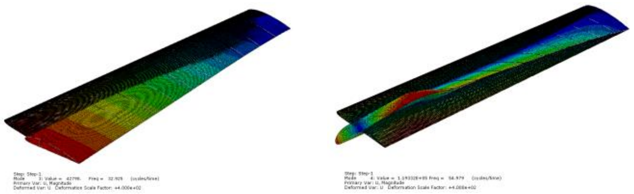
Fig. 6 Mesh structure of the sample wing

E. Sample Modal Analysis Results

After the finite element model construction process, first 4 mode shapes and corresponding natural frequency values are determined via the Abaqus solver. Figure 7 illustrates the modal analysis results of the sample wing having 350 mm equal rib distance.



Mode-1 [f_1=5.109 Hz] Mode-2 [f_2=30.102 Hz]



Mode-3 [f_3=32.925 Hz] Mode-4 [f_4=54.979 Hz]

Fig. 7 Mesh structure of the sample wing

Mode-1 corresponds to first body bending frequency while torsional frequency of the wing corresponds to Mode-4.

In order to be sure about that these modes will always be stay in the same sequence and in order to be sure about that there will not be any local modes between them, rib spacing values are restricted between 290 mm to 400 mm according to the preliminary analysis results.

F. Parametrization of the Model

During the optimization process various wing models having different wing spacing must be prepared and analysed in a short amount of time. Therefore, the previous finite element model has to be parametrized. It is possible to prepare a parametric finite element analysis model via an in-house Python script for Abaqus solver. Therefore, within the content of this work, an in house Python script is prepared to construct the parametric wing geometry; to define shell sections; to assign the defined sections to the parts; to mesh the independent parts; to assemble the wing by arranging the rib spacing; to define tie interactions between the parts; to define the boundary conditions; to solve the modal analysis in Abaqus environment.

III. OPTIMIZATION PROCESS

The main objective of the optimization process is to maximize both of the torsional frequency and frequency ratio (f_4/f_1) of the wing by changing the rib spacing parameter. Figure 8 summarizes the optimization loop.

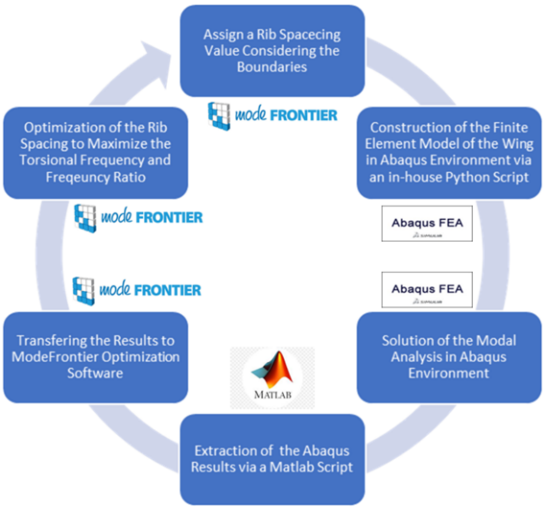


Fig. 8 Optimization loop

The process begins with selection of a rib spacing value between 290 mm to 400 mm by Multi-Objective Genetic Algorithm 2 (MOGA-2) solver of the ModeFrontier. Then, wing model corresponding to selected rib spacing value is prepared and solved via the assistance of the in-house Python script in Abaqus environment. Modal analysis results are saved to a file having an extension of ".dat" by Abaqus. In order to read and evaluate the results from that file, an in-house Matlab script is also developed within the content of this work. That script reads the natural frequency values of Mode-1 and Mode-4, then calculates the frequency ratio. After that, result read by the Matlab script is transferred to ModeFrontier and according to the analysis results ModeFrontier determines the optimum rib spacing value. Figure 9 illustrates the optimization flowchart prepared in ModeFrontier.

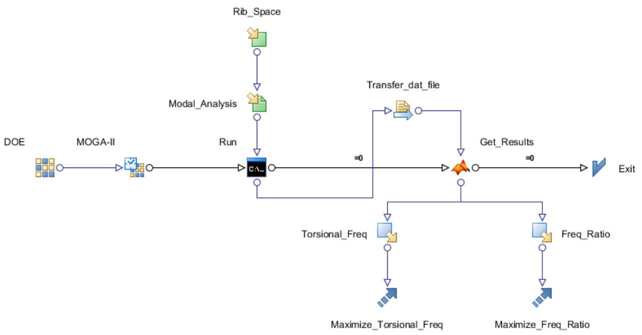


Fig. 9 ModeFrontier optimization flowchart

IV. RESULTS

Variation of torsional frequency and frequency ratio values with rib spacing parameter is determined as a result of the optimization process. Figure 10 illustrates the relationship between the torsional frequency and the rib spacing.

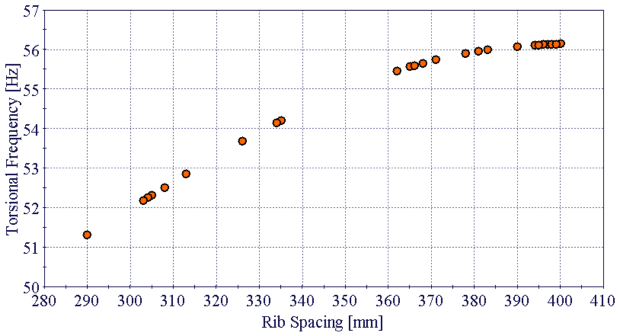


Fig. 10 Variation of torsional frequency with rib spacing

Figure 11 represents the relationship between the frequency ratio and the rib spacing.

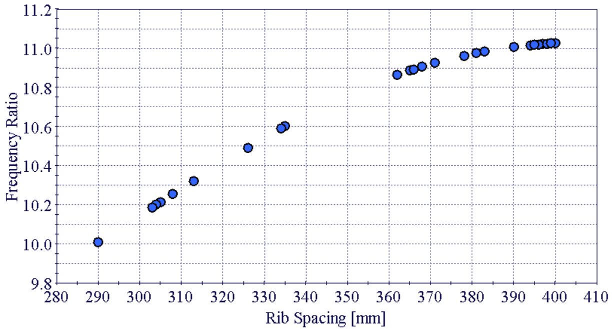


Fig. 11 Variation of frequency ratio with rib spacing

Combined results are also presented in Figure 12.

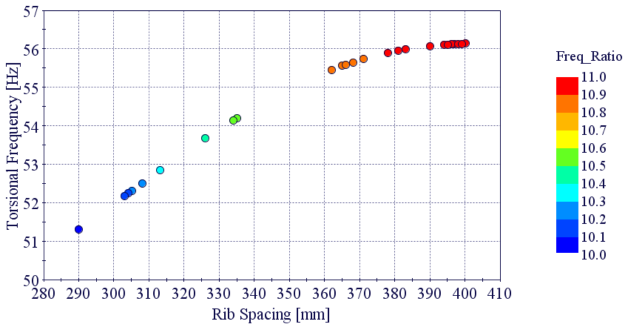


Fig. 12 Variation of frequency ratio with rib spacing

V. DISCUSSION

According to the results the rib spacing parameter has a quite limited effect on the torsional frequency and the frequency ratio. Only a slight torsional frequency and frequency ratio increments are observed with increment of the rib spacing. The main reason behind this result is increment of the rib spacing leads to slight decrement of the first body bending frequency and slight increment of the torsional frequency. As a result, it is observed that, the torsional frequency and the frequency ratio so the flutter speed is maximized by maximizing the distance between the ribs. According to the results 400 mm equal rib spacing is the optimum value for the examined wing.

VI. CONCLUSION

This research covers rib spacing optimization of a generic UAV wing in order to maximize both of its torsional frequency and ratio of the torsional frequency to the first body bending frequency value. A parametric wing model prepared and modal analyses are performed in Abaqus environment. ModeFrontier software is used for the optimization process. Optimization results revealed that rib spacing has a minor effect on both of the torsional frequency and the frequency ratio. Therefore, it is possible to slightly increase the flutter speed of a wing by increasing the rib spacing parameter without changing the weight of the wing.

As a future work it is aimed to make a multidisciplinary multi-objective optimization study to minimize the wing mass while maximizing its flutter velocity and constraining the stress boundaries inside a certain interval.

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