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***Abstract*—Metamaterials introduce innovative possibilities for morphing wing design. This paper explores two methods of incorporating metamaterials into morphing wing design and applies a Multidisciplinary Design Optimization process to optimize and compare this design against a conventional composite wing. The analysis integrates aerodynamic, structural, and control considerations to evaluate the effectiveness of the metamaterial applications. The two approaches involve a variable-stiffness leading edge surface, and a trailing edge equipped with a metamaterial lattice hinge for smooth deformation. The paper presents the Multidisciplinary Design Optimization framework and initial findings from individual analyses, linking two-dimensional aero-structural wing rib design with surrogate models that extend to three-dimensional aerodynamic and control evaluations.**

***Keywords*—metamaterials, morphing wing, multidisciplinary design optimization, unmanned aerial vehicles**

I. INTRODUCTION

Multidisciplinary Design Optimization (MDO) has become a standard in efficient aircraft design. In this paper, we introduce the use of MDO to evaluate new approaches in morphing wings using metamaterials. The metamaterial applications of the morphing wing are recently in the scope of researchers. Wang et al. [1] and Boston et al [2] investigated multi-stable metamaterial wing structures. Wang et al. [3] applied distributed active lattice structures with varied cell geometries to an upper wing surface. Janett et al. [4] proposed a method to design low density, highly compliant wing structure with spatially tuned stiffness. The previously mentioned works were focused on small or micro UAVs. De Gaspari [5] used an MDO approach for a morphing leading edge (LE) on a 50-seater regional aircraft. His aerodynamic and topology optimization led to the design of a compliant rib using super-elastic material NiTiNOL. In contrast to all mentioned publications, we propose two different metamaterial applications for the morphing wing. The first involves implementing a metamaterial structure on the LE surface and utilizing a standard kinematic mechanism as a morphing rib. The surface, with variable stiffness characteristics, is expected to achieve optimal aerodynamic shapes in different flight regimes. Another benefit of this approach is Structure Health Monitoring (SHM) functionality of the wing surface as proposed by Bajer et al. [6], however the SHM was not included in MDO. The second approach, applied to the trailing edge, features a metamaterial lattice optimized to allow rotation of the trailing edge while being stiff enough to carry the normal force loading simultaneously.

A. *Morphing using metamaterials*

Metamaterials can be described as a composition of repeating microscopic cells forming a macroscopic structure, as noted by Zadpoor [7]. Unlike conventional homogeneous materials, metamaterials can achieve unique macroscopic properties, such as negative Poisson's ratio [8],[9] or a spatial properties variation [10], [11]. Homogenization serves as a bridge between the microscopic and macroscopic properties of metamaterials. Successful homogenization requires a clear separation of scales, which may not be possible if the cell size is too large compared to the overall structure. Additionally, the grading of the cells on the macroscopic level impairs the periodicity of the structure. In these cases, full scale simulations are needed to ensure accuracy. If, however, they are fulfilled, various approaches for metamaterial homogenization can be employed. In-plane loading enables to use density-based or simplified geometry model [12] or computation of the effective elastic moduli by real geometry model comparison [13]. When considering moderate or large deflections, the structural response exhibits more complex behavior, such as coupling effects between longitudinal and transversal directions [14], [15].

B. *Multidisciplinary design optimization*

One of the first research on MDO was carried by a team of Hafka et al. [16] and Sobieszczanski-Sobieski [17]. A comprehensive overview of MDO architectures elaborated Martins and Lambe [18]. The overview covers both monolithic and distributed architectures. A number of the types of presented architectures aim to an idea, that MDO should be always setup individually to a given design. The important aspect of saving computational time in MDO is use of surrogates or response surface methodology (RMS) [19]. More recent works brought a focus on mission or flight performance module in MDO such as Afonso et al. [20] and Albuquerque et al. [21]. Regarding the mentioned literature search, the MDO will lead to 2-level MDO with using Response Surface Methodology (RSM) as surrogates to reduce the computation time connected to various analyzed flight regimes.

C. *Involved disciplines*

The essential interdisciplinary coupling in metamaterial assessment involves fluid-structure interaction at the wing rib level. Morphing structures are modeled as 2D rib structures. The Finite Element Method (FEM) is the most common approach for analyzing the structural loading and deformation of the wing rib. Structural loading must be balanced with aerodynamic loading, which can be determined by low or high fidelity aerodynamic analyses, and actuation forces from control analyses. These aerodynamic and control analyses should be applied across the entire wing, taking into account the span effects.

D. *Research goal*

The research goal of this paper is to set up MDO for the morphing wing. This setup will allow for the comparison of morphing wing design with a standard composite wing design, both in their optimized states. To achieve this, we use typical UAV characteristics with an MTOW of 50 kg and a rectangular wing of the same shape and size as used in the CHANGE project by Werter et al. [22] and later in the SmartX project by de Breuker et al. [23]. These UAV characteristics enable us to assess the wing design in various flight regimes under trimmed conditions. The MDO includes 2D aero-structural analysis at the rib level and control and aerodynamic analyses at the wing and UAV levels. A conceptual design of the wing segment design is depicted in Figure 1. The metamaterials are applied on LE surface and TE lattice hinge. Optimal stiffness distribution of homogenized characteristics is going to be searched within the MDO. The homogenized characteristics are merged to a beam in the 2D structural analysis. The lattice placed at the TE hinge position is going to be analyzed on the microscale level as shows Figure 3. Elastic silicone-based foil is considered for the TE surface, however loading from different TE deflection between adjacent ribs is not included in the MDO.

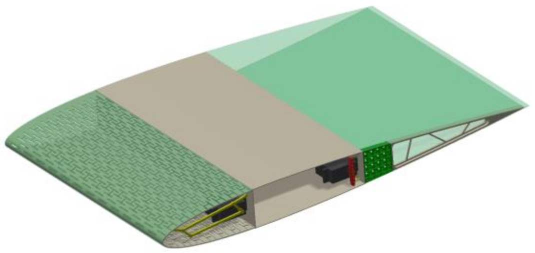

Figure 1: Visualization of morphing wing segment using metamaterials applied on leading edge surface with variable stiffness and trailing edge lattice hinge

II. METHODS

Single discipline analyses used in the MDO are introduced at first in this chapter. Then, the section continues with MDO architecture description.

A. *Single disciplines analyses*

1) *Aerodynamics*

The aerodynamic performance evaluation of airfoils is based on the widely known and applied XFOIL analysis tool developed by Drela at MIT [24]. This tool integrates a panel method with a viscous boundary layer model to provide predictions of the aerodynamic properties of the airfoil, such as lift, drag and pitch moment coefficients, as well as the pressure distribution over the airfoil. XFOIL is capable of simulating both laminar and turbulent boundary layers as well as predicting the transition between these types of boundary layers. The tool is widely used in both academic and industrial environments due to its balance between accuracy and computational efficiency.

The aerodynamic properties of the wing are evaluated using the AeroSandbox (ASB) toolbox [25] implemented in the Python language. This toolbox integrates numerous low-fidelity methods for wing and aircraft analysis. It also provides an environment for gradient based optimization of the wings and airplanes based on an algorithmic differentiation approach. In this work, we use a lifting line method integrated in ASB with modification for non-zero sweep and dihedral angles capable of analysing multiple wing configurations. The wing profile drag is usually included in the aerodynamic analysis either by direct XFOIL calculation or by NeuralFoil [26] estimation (neural network pre-trained on the XFOIL calculations) in a defined spanwise wing section. However, in the MDO process, the ASB reads airfoil characteristics from surrogates defined by aero-structural analyses for each design vector.

2) *Structural LE*

Implementing meta-materials in the morphing wing design requires multi-disciplinary modelling approach due to the generally anisotropic and heterogeneous behavior of these structures. They are valuable for their large bending flexibility which can be tailored according to the structural requirements. Such meta-material is shown on left side of Figure 2. The bending and tensional stiffness is driven by changing the governing geometry parameter w_1. For the optimization purposes, the LE geometry is simplified to the in-plane problem described by finite-strain large deformation Timoshenko beam theory, where homogenized material parameters are extracted by using quadratic element interpolation functions for known internal forces and deformations of the real geometry model computed in ANSYS 2021 R1. The nonlinear material data, the transverse Poisson ratio effect and the geometric nonlinearities are considered. The kinematic mechanism is based on the study [27], [28] where the kinematic mechanism consists of simple rods connected with joints and it has 1 degree of freedom, see on right side of Figure 2.

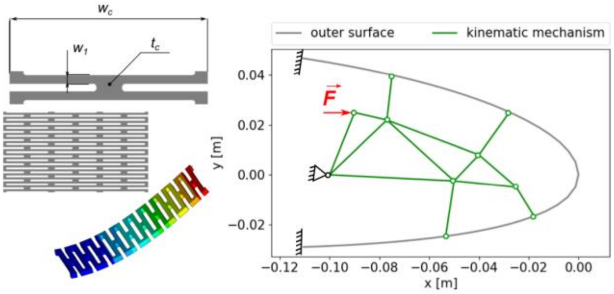

Figure 2: LE geometry and metamaterial model

3) *Structural TE*

The goal of the TE is to create a hinge-like structure similar to the one presented by Liu et al. [29] by using meta materials instead of a homogeneous material. However, due to the overall wing dimensions and manufacturing limitations, the separation of scales cannot be granted. Therefore, a fullscale finite element analysis is employed to predict the structural mechanical behavior. To maintain a reasonable computational cost for the full-scale analysis, two adjustments are considered: first, the problem is approximated as two-dimensional, and second, beam elements are utilized in place of continuum elements. Another challenge arises due to the complex material behavior of the superelastic material Nitinol, which is chosen due to its high strain recoverability. To account for this, the nonlinear material capabilities of ABAQUS 2023/Standard (*Dassault Systèmes Simulia Corp., Providence, RI, USA*) are used in conjunction with a custom user material. The geometry is represented by cells consisting of one-dimensional splines, which are parametrized by a drill angle, as shown in Figure 3 (a). This angle is subsequently graded using another two-dimensional spline, shown in Figure 3 (b) to create the macroscopic structure, shown in Figure 3 (c). This approach follows the work of Zwar et al. [30] and reduces the number of parameters needed to describe the whole structure, which is beneficial for the optimization process.

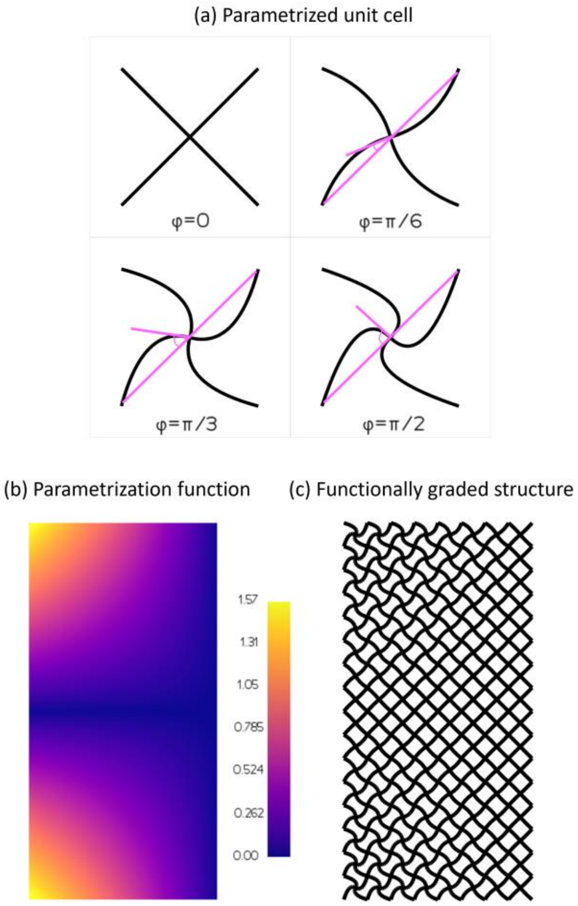

Figure 3: TE Lattice design

4) Control

The control analysis follows the 3D aerodynamic analysis, which provides spanwise lift distribution and TE deflection in the analyzed flight regimes. The control analysis's main objective is to design servos to enable morphing wing control while minimizing the weight of actuators. This goal is achieved by selecting actuators based on the maximum loading from all analyzed flight regimes. The flight regimes include symmetric regimes from aerodynamic analysis and roll maneuvers. Pure rolling motion, as described by Phillips [31], is applied to check roll requirements. The roll requirements are derived from CS-VLA [32], specifying the maximum time for a 30-degree bank turn to reverse into a 30-degree bank in the opposite direction. Control allocation is implemented due to the morphing wing's capability to vary TE deflection along the span. Roll control effectiveness is estimated using a linear function calculated from the lift slope multiplied by the lever arm of the wing segment to the roll axis.

Daisy chaining control allocation is a simple method of distributing the pseudo control input across multiple actuators. When an actuator becomes fully saturated, the remainder of the pseudo input is sent to the next actuator. This repeats until all actuators are saturated or the input was allocated and there is no input to send further, making other actuators unaffected [33]. The Daisy chaining control allocation method was modified to minimize differences in deflection between neighboring TE ribs, as excessive differences in deflection can induce high tension in the TE flexible surface. Saturation was replaced with an artificial limit on the maximum difference in TE deflection between adjacent ribs.

Only slow changes are expected in the morphing of the LE, which is intended to remain constant along the span. Two actuator design variants are analyzed: the first involves a single servo located in the fuselage to power the entire LE, while the second uses a separate servo for each morphing LE rib. The lighter of the two actuator designs will be selected.

B. MDO Architecture

The MDO architecture aligns with the overall goals of the BAANG project [34], which are defined as a morphing wing demonstrator and morphing wing design. The demonstrator is intended to be a wing section bounded by two ribs, showcasing the technology and undergoing wind tunnel tests. The initial MDO is common for both project goals and therefore focuses on single-rib optimization, with extensions to spanwise aerodynamic optimization and control analysis to evaluate the objective function. After the first stage of MDO, the demonstrator will be designed in detail and manufactured. However, the wing design should continue to incorporate spanwise characteristics in the MDO process. The proposed MDO architecture in Figure 4 is visualized using XSDM visual representation defined by Lambe and Martins [35].

The MDO process begins with a design vector that describes the simplified geometry of the leading and trailing edges. The LE description includes the definition of the kinematic mechanism, detailing joint positions and the dimensions of the connecting rods. Homogenized stiffness characteristics of the LE surface are defined along both the upper and lower wing surfaces, extending from the LE to the fixed wing box. A different approach is used for the TE design. The design vector includes parameters describing the lattice geometry, as shown in Figure 3. The geometry is defined by six points, with spline interpolation used between them. The rear part of the TE, attached to the lattice, has predefined dimensions and is not included in the MDO.

All the mentioned parameters have a continuous nature or can be treated as continuous, such as the dimensions of the connecting rods in the kinematic mechanism. This approach is intended to round the final rod designs to the closest match from a wide selection of aluminum rod semi products. However, the number of ribs along the span is a discrete parameter and has been excluded from the design vector. For the initial MDO, five ribs per half-span were chosen. The MDO will then be repeated with different numbers of ribs to optimize this discrete parameter.

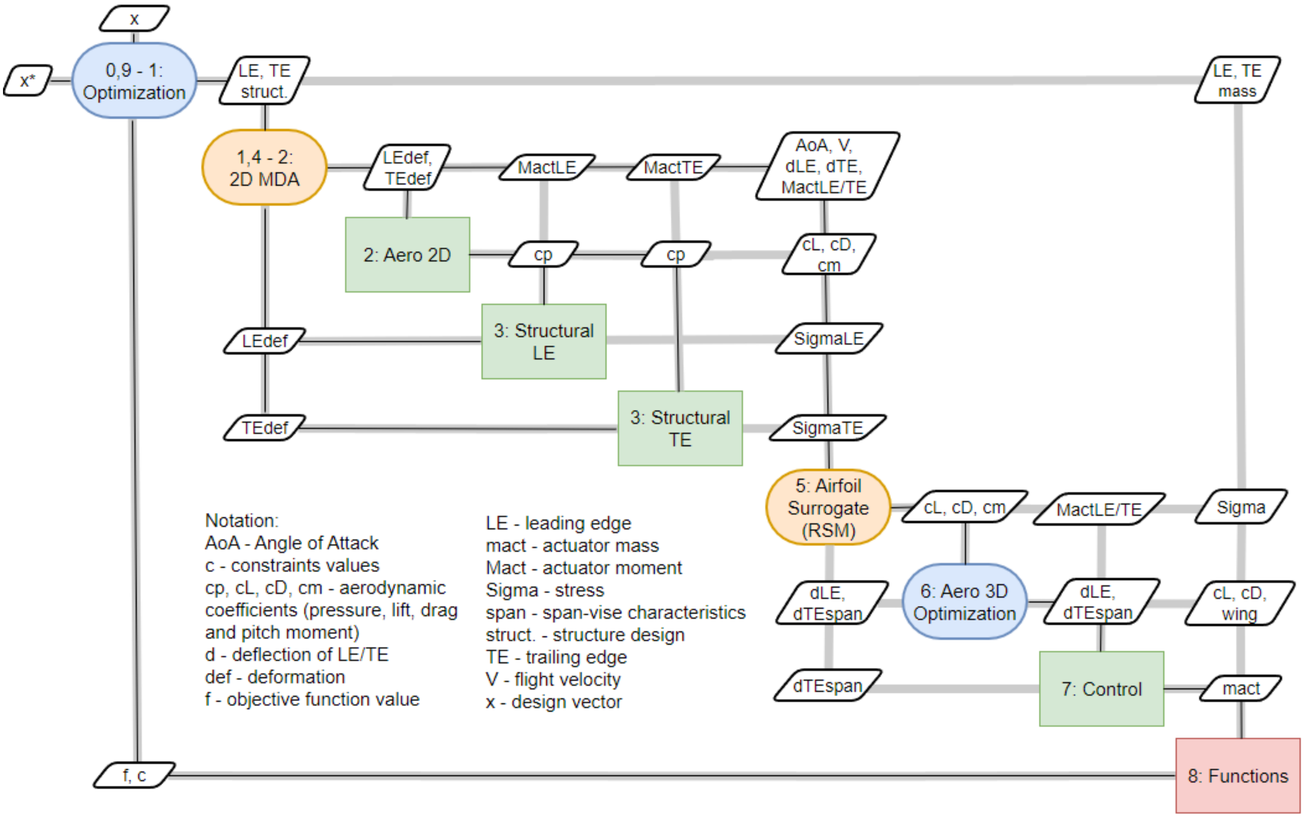

Figure 4: XDSM visualization of proposed MDO architecture

The first optimization block, labeled 0, represents the main MDO loop. The proposed architecture is implemented in OpenMDAO software [36], which manages the primary MDO loop. The following Multi-Disciplinary Analysis (MDA), labeled 1 in Figure 4, is a loop for 2-dimensional aero-structural analyses of a wing section. This loop is repeated for 25 cases defined by central composite design with four factors: Angle of Attack (AoA), flight velocity and LE and TE deflections. Since only small deflections around 10 degrees are considered, a quadratic response surface methodology (RSM) in block number 5 is expected to provide good balance between the modeling accuracy and computational expense. The RSM is constructed for aerodynamic coefficients c_L, c_D and c_m, for actuators moments and for maximum stress of LE and TE components as a function of the four factors. At this stage two analyses utilize these rib surrogates at the wing level.

Block 6 provides optimal wing spanwise characteristics in regimes necessary to evaluate constraints and objectives. Another goal of the analysis is to ensure that the UAV can achieve its maximum lift coefficient. Block 7 assesses roll requirements and determines the size of the morphing actuators. The final block, labeled 8, includes both constraint and objective functions. Constraints limit structural loading based on material characteristics. The objectives are derived from the maximum range (R_{max}) and endurance (E_{max}) equations for battery-powered aircraft. Both maximum range and endurance are proportional to the ratios of battery mass (m_{batt}) to the maximum take-off weight (m_{TOW}) of the UAV. Battery mass varies inversely with wing mass, as any change of wing mass is reflected in the battery mass, given that the UAV's maximum mass is fixed.

$$R_{max} \approx \frac{c_L}{c_D}\frac{m_{batt}}{m_{TOW}} \qquad (1)$$

$$E_{max} \approx \frac{c_L^{3/2}}{c_D}\frac{m_{batt}}{m_{TOW}^{3/2}} \qquad (2)$$

Both parameters are included in objective function with invers value and combined using weighted sum.

III. RESULTS

The MDO setup is in the implementation process recently. Therefore, only preliminary single disciplinary results are provided in this section. At first, results of aerodynamic optimization applied to an original wing with NACA 2512 airfoils is introduced, then some results from LE structural analysis concludes this section.

To estimate the potential benefits of wing morphing on aerodynamic performance, a preliminary aerodynamic shape optimization was performed using the lifting line method and the NeuralFoil tool implemented in AeroSandbox (ASB). The wing shape parameters used to vary the morphing parts of the wing were defined using the Class/Shape Function Transformation originally proposed by Kulfan [37] and implemented in ASB. To account for camber morphing while considering a fixed wing box shape, the parameterization was modified according to the method developed by de Gaspari [38].

The optimization results suggest that the cruise performance of the trimmed wing-horizontal tail configuration, in terms of glide ratio, could be improved by 14%, while the loiter performance, in terms of endurance parameter, could be improved by 9%. These improvements are compared to the performance of the initial wing-horizontal tail configuration under certain flight conditions. It is important to note that the results presented may be overestimated due to the limitations of the methods used. The resulting optimum aerodynamic shapes are shown in Figure 5.

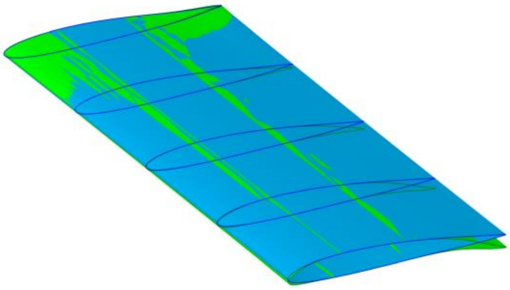

Figure 5: Optimal aerodynamic shape of the wing in cruise condition (blue) and loiter condition (green)

The preliminary analysis of the LE rib resulted in deformed geometry of proposed LE design with the metamaterial surface and kinematic mechanism. The simplified Timoshenko beam-based model was solved by using linearized matrices and line-search method [39] for the homogenized material parameters E = 200 MPa, μ = 0.3, 10 cells laterally (w_c = 20 mm, t_c=1.2 mm, w_1 = 0.5 mm) and loaded by F = 0.4 N. The initial and deformed geometry is depicted in Figure 6.

IV. CONCLUSIONS

This work aims to evaluate two new metamaterial applications for a morphing wing: a variable-stiffness leading edge and a lattice hinge at the trailing edge. These approaches show potential for enhancing both aerodynamic performance and structural efficiency. Due to the complexity of the morphing wing design, we propose an MDO to optimize the design. This article presents the MDO architecture along with preliminary single-discipline results. The MDO architecture utilizes advanced computational tools such as ABAQUS, AeroSandBox, and OpenMDAO. Specifically designed for the morphing wing using metamaterials, the architecture combines 2D aero-structural analyses with 3D aerodynamic optimization and control analysis, optimizing a single rib at the 2D level and actuators for the entire wing. As a next step, after the MDO convergence, we plan to expand the design vector to include spanwise design parameters and run the MDO again, aiming to achieve an optimal design for the entire UAV wing.

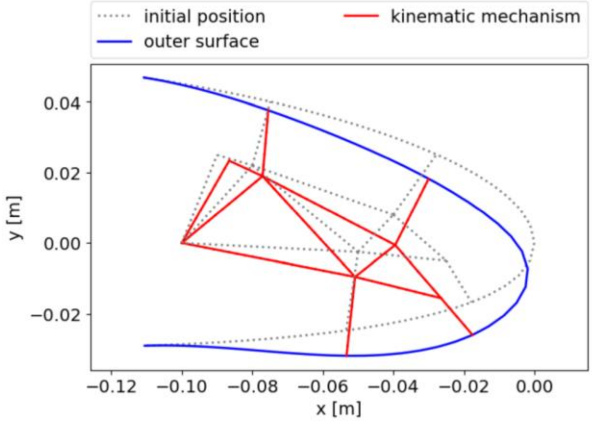

Figure 6: Deformed geometry of the FEM Timoshenko beam model

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