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Review of the doctoral dissertation

by Ramesh Kumpati, MSc Eng., entitled:

Optimization method for ultralight aerial composite structures

Dissertation supervisor: Wojciech Skarka, PhD, DSc, Eng., Prof SUT

1. Legal basis and subject of the review

The review was made on the basis of the resolution of the Council of the Discipline of Mechanical Engineering of the Silesian University of Technology (SUT) in Gliwice of 23.10.2024.

The subject of the review is a doctoral dissertation entitled "Optimization method for ultralight aerial composite structures", authored by Ramesh Kumpati, MSc. The scientific discipline of the doctoral thesis is Mechanical Engineering.

2. Evaluation of the layout of the doctoral dissertation

The dissertation, which has 173 pages, is written in English, consists of 8 chapters, an abstract in Polish and English, a bibliographic list of 148 items, a list of figures, tables and a list of symbols and markings used in the dissertation.

Chapter 1

The chapter introduces the issues of optimization of composite materials used in the aviation industry, in particular in UAVs (Unmanned Aerial Vehicles). The doctoral student presented the objectives of the dissertation, the scope of research and the scientific problem. The aim of the dissertation is to optimize composite materials in terms of ensuring proper geometry, strength and stiffness of the UAV vehicle structure while reducing the vehicle's weight, which ensures higher energy efficiency and extend the flight time. The author defines a scientific problem as the need to create a methodology that enables the design of optimized aircraft structures using composite materials while meeting mechanical, environmental and technological requirements. The chapter also contains an overview of the author scientific achievements, including publications in the field of material tests, optimization methods and cases involving UAV design and validation activities.

Chapter 2

The chapter presents a review of references on optimization methods, including parametrical, geometrical and topological optimization. The author also discussed the theory of classical laminated structures, taking into account the buckling problems of the structure (linear and nonlinear models), which is the basis for analyses in the field of composite materials. The author pays special attention to the use of natural fibers such as jute and their mechanical properties compared to synthetic materials. The chapter provides an overview of the latest developments in the field of genetic algorithms used in multi-criteria optimization.

Chapter 3

In the chapter, the author formulates a research methodology taking into account the process of material selection, geometry design and the strategy of multi-criteria optimization with the use of genetic algorithms (GA) in relation to UAVs. The developed methodology includes:

- Selection of bio-composite materials, such as jute and glass fibre composites,
- The process of geometric modeling, in particular the creation of 3D models of structures, such as UAV wings and T-type connectors,
- Multi-criteria optimization strategies using genetic algorithms for structural parameters such as weight, geometry, and mechanical strength,
- Load analysis including the definition of boundary conditions and loads used in structural analysis,

- Design of sandwich structures, in particular the development of composite laminates with different fibre orientations and thicknesses.

Chapter 4-5

The chapters contains numerical and experimental results related to the key UAV components as follows:

- The wing's supporting structure was optimized using composite material and reinforced with T-type joints. As a result of the optimization, a package of alternative recommendations was obtained to improve the mechanical strength and rigidity of the wing, as well as to reduce its mass.
- Optimization of structural cores of wing layer spacers, where the variable of the numerical experiment is the geometric configuration
- Design and optimization of the wing skin of a UAV (model TS-17) with integrated photovoltaic cells. The Author used the homogenization method, which made it possible to analyze the mechanical properties of the wing material depending on the fiber volume. Different plating configurations, including sandwich structures, were analysed.

Chapter 6

This chapter presents the process of manufacturing bio-composites and the validation of material samples using mechanical tests. The experimental data obtained, such as the results of the compression, tension and three-point bending tests, show agreement with the simulation results. The author also presents a discussion on the defects and mechanisms of damage to composites, such as delamination of fibers.

Chapter 7

The chapter contains a summary of the analysis of experimental and simulation data, including:

- Optimization of T-type joints and their strength properties.
- Experimental results for composite panels with interleaved layers.
- Analysis of the mechanical strength and buckling of composites.
- Optimal laminate layering sequences and fibre orientations.

The author demonstrates an improvement in the mechanical strength of the composite materials used, including jute and e-glass (electric glass), while reducing their weight as a result of the application of multi-criteria optimization using genetic algorithms.

Chapter 8

The results obtained as a result of numerical and experimental research conducted by the author in the dissertation confirm the research hypothesis. Optimised ultra-lightweight load-bearing structures made of biodegradable composites have demonstrated their suitability for UAV construction. The research carried out included optimization analyses, ANSYS simulations, test sample preparation processes, and laboratory test procedures. The chapter summarizes the three cases analyzed in the dissertation, focusing on different composite materials: epoxy-jute, epoxy-glass and sandwich structure.

- The epoxy-jute composite showed deformations in the range of 0.022-2.038 mm. Von Mises stresses were in the range of 45.6–5.8 MPa, indicating a variable stress distribution in the material and the most favorable mechanical properties in the context of high compliance, buckling resistance, and minimal risk of damage under working loads.

- The epoxy-glass composite was characterized by lower deformations (0.022–2.302 mm) and stress values in the range of 42–5.5 MPa. The reserve factor (RF) used in the strength analysis of the structure (the ratio of the allowable stress or load to the actual stress occurring in the structure) remained low, which meant a minimal risk of exceeding the permissible loads.

- The sandwich structure had the highest deformation values (1.984–2.302 mm), stresses in the range of 57.7–5.8 MPa, nevertheless showed lower buckling resistance compared to composite laminates.

The optimization results indicate that the final type of composite material depends on the application requirements:

- If buckling strength and weight minimization are prioritized, a sandwich structure is the best solution.
- If the goal is to balance cost and mechanical performance, epoxy-glass laminate seems more suitable.

The results suggest further studies on changes in geometry, fibre orientation and layering sequences, which could improve the structural strength of UAVs.

3. Dissertation main achievements

The doctoral dissertation is a comprehensive study on the optimization of composite materials and the geometry of UAV carrying structures. The dissertation is an ambitious interdisciplinary undertaking that combines materials engineering with advanced optimization methods taking into account ecological aspects.

The most important achievements of the dissertation include:

a) Development of an innovative method for multi-criteria optimization of the properties of the UAV vehicle support structure using genetic algorithms. As a result of the use of multi-criteria optimization, it is feasible to increase the strength properties of the UAV wing structure while reducing its weight. The application of genetic algorithms in combination with the classical theory of composite materials in the context of UAV construction is an important scientific contribution.

b) Experimental validation of bio-composite materials, which included mechanical tests (compression, tension, three-point bending) carried out in accordance with ASTM D 3410-03 and fractographic analysis of the evaluation of fibers of samples that have failed. Tests demonstrated simulation compliance and high strength of bio-composites compared to hybrid and synthetic materials. The test results provide a valuable summary and inspiration for other researchers.

   - Natural Fiber Composites Group

   Jute/Epoxy is a biodegradable composite made of natural fibres, characterized by ecological character and moderate mechanical strength, as well as bio-resin used as a matrix in combination with natural fibres.

   - Hybrid Composites Group

   Jute-Glass/Epoxy in different glass and jute fibre configurations, e.g. 75% jute + 25% glass and 25% jute + 75% glass, showing improved strength compared to pure bio-composites, but still retaining ecological benefits

   - Synthetic Composites Group

   Glass/epoxy as an example of a classic composite synthetic with high mechanical strength and toughness, as well as sandwich structures consisting of a core made of PVC foam in combination with glass and jute fibres, with the best strength-to-weight ratio

c) Demonstrate that bio-based composites, such as jute and glass fibre laminates, can be an effective alternative to traditional synthetic materials (e.g. carbon fibre) by meeting mechanical requirements while reducing weight and increasing environmental sustainability.

d) Application of the multiscale model (cf. Fig. 28), which integrates the macro scale (construction) with the micro scale (material properties). During the evaluation of composite materials at the micro scale, the criteria of Fiber Failure (FF) and matrix failure (MF) were considered.

e) Optimization of the strength and flexibility of the UAV wing structure in terms of the installation of photovoltaic cells.

f) A comprehensive interdisciplinary approach taking into account the discipline of materials engineering, structural optimization methods and experimental validation, which makes such an approach a valuable contribution to both engineering science and practice.

4. Substantive evaluation of the dissertation

An interesting research and utilitarian aspect of the dissertation is the definition of the multi-criteria optimization task, combining FEM model (Finite Element Method) model with a numerical experiment and limitations resulting from the technology of producing biodegradable composite materials.

In the task of multi-objective optimization of composite structures, the MOGA (Multi-Objective Genetic Algorithm) model was used, based on a genetic algorithm, which iteratively searches for the best solutions by simulating the processes of biological evolution (selection, crossing, mutations). The model takes into account a number of constraints that ensure compliance with the actual structural and strength requirements. The process of multi-criteria optimization was preceded by the definition of the goal function and constraints:

i) Design Limitations:
   - Design variable: Orientation angles of laminate layers.
   - Fixed parameters: Fixed composite material, sample geometry, boundary conditions, and discretization of the angle of the material layers {0°, 30°, 45°, 60°, 90°}

ii) Goal Features:

- Minimization of the total number of plies.
- Minimization of the total weight of the laminate
- Minimization of the Inverse Reserve Factor (IRF).
- Minimization of the Deformation Load Multiplier (DLM).
- Minimization of the Buckling Load Factor (BLF)

By introducing restrictions that the permissible load of the structure cannot be exceeded, and at the same time the structure should be stable under the given load. The parameters that remain constant in the optimization process are the properties of the composite material, the geometry of the sample, boundary conditions, discretization of the angles of the laminate layers relative to each other. The result of the optimization task was a set of Pareto-optimal solutions that provides a compromise between different criteria. The optimization results were experimentally confirmed by mechanical tests (e.g. tensile, compression, bending tests) and numerical analyses (finite element method). The author analyzed three main cases of optimization of loads the UAV:

- Optimization and analysis of T-joints by developing four geometric variants of T-joints, differing in material (jute, e-glass, PVC foam) and shape (with and without hole). Finite element simulations in ANSYS and mechanical tests (compression, tension, bending) were performed. Optimization of the joint geometry reduced stresses in key areas such as the stringer's contact with the base. In addition, the connection design with PVC foam as the core achieved the best results in terms of strength and weight.

- Optimization of z-core layer structures for high rigidity with minimal weight. The Author analyzed seven core configurations (variables: height, angle, thickness), and also conducted static and quasi-static simulations in ANSYS software (e.g. three-point bending tests). Structures made of e-glass achieved higher values of critical buckling load, but jute offered a favorable compromise between strength and ecology. Core optimisation reduced the weight of the structures while maintaining their mechanical properties.

- Optimization of the wing of a UAV with built-in photovoltaic cells in three variants: **(i)** a photovoltaic cell between layers of glass fibers, (ii), a cell under a layer of polyurethane and glass fibers, and (iii) a cell on the surface of the laminate without protection. Mechanical simulations and endurance tests were carried out. Laminates with a layer of polyurethane provided the best protection of the cells against mechanical damage. The integration of the cells increased the functionality of the UAV with minimal weight increase.

The dissertation of Ramesh Kumpati, M.Sc., Eng., is an important contribution to the research field of optimization of geometric and strength properties of composite structures intended for the production of UAV. The author presented an interdisciplinary approach, combining materials engineering, advanced optimization methods and attention to ecological aspects, as well as selected challenges of design, simulation and experimental investigations. The developed methods and research results have potential applications also in other sectors of the economy, such as the automotive and energy.

5. Critical remarks

5.1. The dissertation considers only static load cases of UAVs without taking into account the overload related to the dynamics (take-off/landing/turning) and cyclical loading, as well as the memory and accumulation of material fatigue during the regular operation of a UAV. In the case of UAVs, fatigue analysis is crucial, because the wings and fuselage are subject to random aerodynamic loads. Validation using simulation or experiment would allow the fatigue life of structures to be assessed under conditions of dynamic load history, including the determination of the number of cycles to material failure. In the context of fatigue strength, it is worth considering an energy approach that will take into account the specificity of composite materials, including their anisotropic properties, delamination, separation of fibers from the matrix and other damage mechanisms.

5.2. Chapter 6 of the dissertation (Manufacturing of bio-composite and validation) reports the static validation of the mechanical strength of material samples according to ASTM D3410-03. However, the dissertation does not present an assessment of fatigue strength, where the samples would be subjected to multiple cyclic or random loads, in a manner similar to UAV operating conditions. Does the author consider to continue fatigue tests of selected composite materials, e.g. in accordance with ASTM D3479?

5.3. The author repeats fragments of the description of the role of multi-criteria optimization and the use of ANSYS Workbench (Page 138 vs. Page 49). The first fragment uses the term "plies" (layers), while the second fragment uses "laminas" interchangeably. Both fragments repeat the same key information about optimization, i.e. that the optimization result is a Pareto front representing trade-offs between criteria, and that ANSYS Workbench integrates with the multi-criteria optimization algorithm in the optimization process.

5.4. The author summarizes (Page 49): "MOGAs (Multi-Objective Genetic Algorithms) provide a Pareto front, which provides engineers with a thorough understanding of design trade-offs, allowing them to make more informed decisions". However ultimately in the dissertation the author does not present the aforementioned Pareto curve(s), while summarizing the results of optimization studies in Tables 26-29.

5.5. The author does not discuss the operational aspects of the proposed materials, such as flammability and resistance to chemical agents (e.g. agricultural applications) and does not consider the effects of aging of materials during the operation of an UAV (e.g. accelerated aging tests of composites).

5.6. The dissertation lacks a broader background and discussion of similar scientific projects and commercial solar-powered UAVs, e.g. AeroVironment Helios, Facebook Aquila, SolarXOne.

5.7. Contour diagrams reporting the results of simulation calculations have illegible markings due to too small font size.

6. Final conclusion

In his doctoral dissertation entitled "Optimization method for ultralight aerial composite structures", Ramesh Kumpati, M.Sc., Eng., completed the research work and demonstrated the knowledge and competence required to obtain the degree of doctor of technical sciences. Moreover, the results of the dissertation are applicable in industrial practice.

The dissertation of Ramesh Kumpati, MSc, is an innovative approach to the multi-criteria optimization of the geometry and mechanical properties of composite material, taking into account both weight reduction and improvement of mechanical strength. The results of experimental and numerical research work confirm the effectiveness of the developed design methodology. In addition, the dissertation evaluates the potential of bio-composites as an ecological alternative to traditional engineering materials. The developed optimization strategies can be used for further development of other UAVs.

I hereby state that the dissertation of Ramesh Kumpati, M.Sc., Eng., meets the formal requirements for doctoral dissertations set out in Article 187 of the Act of 20 July 2018, Law on Higher Education and Science in Poland (Journal of Laws of 2022, item 574, as amended). I hereby request that the dissertation be admitted to public defense in the discipline of Mechanical Engineering. The critical remarks I have formulated do not affect the overall positive assessment of the dissertation.

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