Heliyon 10 (2024) e24151

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Aeroelastic tailoring for aerospace applications

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ARTICLE INFO

Keywords:
Aeroelastic tailoring
Aeroelasticity
Aerospace applications
Flutter mitigation
Aeroelastic optimization
Passive aeroelastic control

ABSTRACT

This study presents a brief account of the seminal works on aeroelastic tailoring for aerospace applications. Tailoring using advanced composites is a revolutionary process in the ever-evolving realm of aerospace design. The rapid growth in scientific knowledge and research necessitates the consolidation of the latest research and technological advancements every few years. The current work is part of this process. The major portion of the study covers the latest developments and state-of-the-art research in this century, with a special focus on the last ten years. However, a brief account of the historical background, the theoretical foundation, and a few seminal works from the later part of the previous century and the early part of this century have also been included to form a comprehensive starting point for new researchers entering the field of aeroelastic tailoring and to assist them in identifying the directions of their future endeavours. A critical evaluation of different research contributions, including their advantages, limitations, and prospects for future work, has been presented. Emphasis has been laid on flutter mitigation and aeroelastic optimization for passive aeroelastic control. New material and structural technologies (like curvilinear fibres, tow steering, functional grading, thickness distributions, selective reinforcing, additive manufacturing, and unconventional structural configurations), and novel tailoring optimization techniques (like lamination parameters, blending constraints, active aeroelastic wing design, shape functions, surrogate modelling, reduced order modelling, uncertainty quantification, matrix perturbation theory, modal-strain-energy analyses, and multiple indigenous optimization algorithms) have been identified as active research areas and prospective enabling tools for future work. The challenges faced in the full-scale employment of aeroelastic tailoring include quick, robust, and cost-effective optimization to cater for all design variables and constraints, experimental validation of new methodologies, certification of new material and structural configurations through relevant bodies and standards and gaining the confidence of industrialists for investment in technologies with a few highly focused areas of applications.

1. Introduction

Aeroelasticity deals with structural members' dynamic and static behaviour in a fluid flow. In aerospace engineering, aeroelasticity deals with the relationship between an elastic structure's deformation while experiencing an airflow and the resultant aerodynamic

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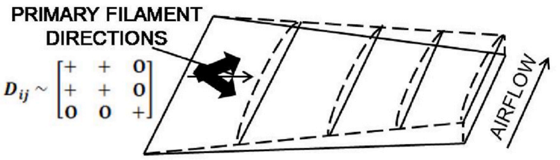
https://doi.org/10.1016/j.heliyon.2024.e24151
Received 2 September 2023; Received in revised form 5 December 2023; Accepted 4 January 2024

force. “Aeroelastic flutter is a dynamic instability of a flight vehicle associated with the interaction of aerodynamic, elastic, and inertial forces” [1], which involves vibrations with growing amplitude that can cause a cataclysmic structural breakdown. “Aeroelastic tailoring is the embodiment of directional stiffness into an aircraft structural design to control aeroelastic deformation, static or dynamic, in such a fashion as to affect the aerodynamic and structural performance of that aircraft in a beneficial way” [2]. Different areas of a structure boast different requirements; for example, strength is paramount for the wing root, while flutter is critical for the wing tip region. Aeroelastic tailoring mostly involves the use of composite materials because they exhibit light weight, elevated stiffness-to-weight and strength-to-weight ratios, and directional stiffness properties. This phenomenon usually makes use of material properties, stacking sequences, and fibre orientations to achieve varying characteristics over different regions of the same structure. This results in bending-torsion coupling for the achievement of different performance objectives, e.g., improved flutter speed, enhanced strength, improved lift, and reduced drag, along with weight reduction intrinsic to the process.

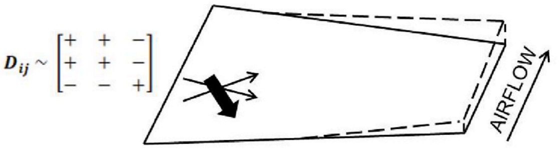
The rapid growth in scientific knowledge and research necessitates the consolidation of the latest research and technological advancements every few years. The current work is part of this process. Jutte and Stanford [3] presented the last comprehensive review on aeroelastic tailoring in 2014. This work aims to consolidate the latest developments and state-of-the-art research in the last ten years, i.e., since the last major review. However, a brief account of the historical background, the theoretical foundation, and a few seminal works from the later part of the previous century and the early part of this century have also been included to form a comprehensive starting point for new researchers entering the field of aeroelastic tailoring and to assist them in identifying the directions of their future endeavours. Emphasis has been laid on flutter mitigation and aeroelastic optimization for passive aeroelastic control. The overview has been divided into three sections: the first one briefly covers the introduction and historical background from the 1950s to the early 1970s; the second concisely covers the growth and maturity of the aeroelastic tailoring concept from the 1970s to the early 2000s; and the third covers the latest developments and state-of-the-art research in this century, with a special focus on the last ten years. Sections 2 and 3 have been divided into sub-sections based on development approaches. A critical evaluation of different research contributions, including their advantages, limitations, challenges, and prospects for future work, has been embedded throughout the study and presented in a separate critical discussion section.

1.1. Historical background

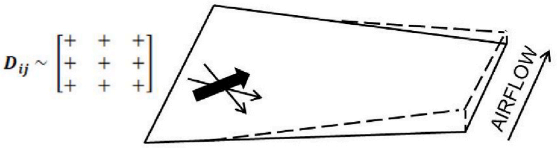
The concept of aeroelastic tailoring was applied about seven decades ago, in 1949, by Munk [4], who oriented wood fibres in a patented wooden propeller design to achieve favourable deformation of the propeller blades with increasing loads. The concept was applied sparsely by a few researchers over the next two decades until it was finally accepted as a new field. Waddoups [5] reported in 1972 that the terminology “aeroelastic tailoring” was first devised in 1969 when the Air Force Flight Dynamics Laboratory (AFFDL) received a plan from General Dynamics to use the directional properties of modern composite fibres for improving the transonic



a. ORTHOTROPIC CHORD – SPAN BENDING COUPLING



b. ANISOTROPIC – BENDING – TWIST COUPLING (WASH-OUT)



c. ANISOTROPIC – BENDING – TWIST COUPLING (WASH-IN)

Fig. 1. An illustration of deformation control possible through laminate design. (a) Orthotropic deflection. (b) Anisotropic deflection (wash-out). (c) Anisotropic deflection (wash-in) (based on Ref [6]).

performance of a supercritical wing, to design the optimum wing form (mainly twist distribution) for an intended manoeuvre as well as cruise.

2. Growth and maturity of the aeroelastic tailoring concept

After the formal inception of the term aeroelastic tailoring, a strong theoretical foundation was built over the next two decades, and different techniques were followed from the 1970s to the early twenty-first century.

2.1. Theoretical foundation

Shirk and Griffin [6] presented an elementary illustration of laminate design to control deformation in 1974, as shown in Fig. 1. In each example depicted, large arrows indicate directions where the percentage orientation of the lamina is the highest. The deflection of the asymmetrical and balanced laminate distribution with an adequate number of plies, like the one in Fig. 1a would be orthotropic with reference to an axis system (generally, the orientation of one axis is along the structural axis of the wing). Symmetrical but unbalanced laminate distributions like the ones depicted in Fig. 1b and 1c would display anisotropic or non-orthotropic deflection, and bending moments would cause wing surface curvature as well as twist. When a nose-down twist is produced due to positive bending, as shown in Fig. 1b, the deformation is termed wash-out. If a nose-up twist is produced due to positive bending, as shown in Fig. 1c, it is termed wash-in. Wash-out and wash-in are also used herein to refer to the stream-wise incidence of a swept lifting surface. A swept-back surface subjected to positive bending demonstrates wash-out, whereas a swept-forward surface would demonstrate wash-in.

Shirk, Hertz, and Weisshaar [2] carried out a comprehensive review of aeroelastic tailoring in 1986, providing a sound basis for further research on aeroelastic tailoring. They summarized the basis and history, the underlying theory, some trend studies, and specific applications of aeroelastic tailoring. Encompassing the ideas and contributions of different researchers, they discussed the use of advanced composites, mathematical optimization procedures, aeroelastic tailoring methodologies, trends, design approaches, and examples of applications of aeroelastic tailoring. Building upon the past and present trends, an outlook on the future applications of the technology was presented. The proposed areas for future development included an increased role of advanced composites in structural design, enhancements in the utilization of aeroelastic tailoring with the inception of advanced design and analysis tools, synergistic integration of passive tailoring and active controls, structural tailoring of large space structures, and formal integration of aeroelastic tailoring in the design process.

Weisshaar [7] presented a review of the primary factors for aeroelastic tailoring employment for the enhancement of flexible fixed-wing aircraft performance in 1987, summarizing the latest trends in aeroelastic tailoring. The use of advanced composite materials for tailoring was envisaged as part and parcel of the evolving design process in an ever-changing world. The areas deliberated

Table 1
Summary of works related to swept-forward wing design.

Year	Author(s) [Ref]	Title	Emphasis	Comments
1981	Sherrer, Hertz, and Shirk [9]	Wind tunnel demonstration of aeroelastic tailoring applied to forward swept wings	Aeroelastic tailoring using advanced composites for improvement in swept-forward wing's divergence speed in sub-sonic regimes. Accurate prediction of the divergence speed for composite and Aluminium plate structures using analytical models based on the formulations of Weisshaar [7] and slender-beam theory. Optimization using the Tailoring and Structural Optimization (TSO) procedure [10] and NASTRAN software. Verification through sub-sonic wind tunnel testing.	The study successfully demonstrated the positive impact of aeroelastic tailoring on the swept forward wing's divergence speed. However, the details of the optimization procedure TSO, developed by AFFDL, are not available. The availability of such details could facilitate researchers working in the domain of aeroelastic tailoring.
1981	Weisshaar [11]	Aeroelastic tailoring of forward swept composite wings	Several closed-form solutions for the ideal static aeroelasticity phenomenon. Static aeroelastic tailoring effect on the span-wise location of centre-of-pressure, lift effectiveness, and divergence, and its application for swept forward wing design. Enhancement in the effectiveness of lateral controls.	The study established the positive effect of static aeroelastic tailoring on various performance parameters. It cautioned about the slight difference between optimum fibre orientations for best divergence speeds and the control effectiveness behaviour of the swept-forward wing design. It also highlighted the opposite response of the control effectiveness behaviour of forward- and aft-swept wings to fibre orientation changes. Future researchers could explore experimental validation of the findings, the effect of fibre orientation on the flutter of forward-swept wings, and the aeroelastic tailoring of aft-swept wings.

upon included control effectiveness, drag reduction, lift effectiveness, static divergence, flutter prevention, and vibration control. A review of terminology used in tailoring, along with formulae characterizing structures with stiffness coupling, was also included. The review concluded with a summary of design characteristics suitable for various aspects of tailoring, illustrating contradictions and concessions to be considered during the design process. The major proposed future advancement area was integrated design, emphasizing the contribution of structural design towards flying qualities, lift curve slope, and the design's economic success. The study also predicted the development of smart structures as an outcome of the integrated design process.

2.2. Swept forward wing design

Early on, the divergence problem of swept-forward wing design caught the eye of researchers in the domain of aeroelastic tailoring. Among the first few, Weisshaar [8] studied the aeroelastic performance and stability properties of aircraft with sophisticated swept-forward composite wing structures in 1978. The study postulated a simplified concept for predicting the divergence behaviour of swept wings with a high-aspect-ratio, made up of laminated composites. The theory was formulated based on the aerodynamic strip theory and the bending theory for laminated beams. The derived governing equations were utilised for predicting wing divergence behaviour with changes in the construction of the laminate. His investigation revealed the possibility of negating the unwanted swept-forward wing divergence behaviour utilizing bending-torsion elastic coupling, incorporated due to coupling parameter K specific to the laminated composites. This counter-balance mechanism is valid over a broad range of angles for swept-forward wings, making swept-forward laminated composite wing design structurally viable. The study laid the foundation for continued research regarding the swept-forward wing design, providing an easy-to-use tool for this purpose.

A summary of other notable works related to swept-forward wing design has been presented in Table 1:

2.2.1. Summary and research needs

The forward-swept wing outperforms the aft-swept wing in terms of manoeuvrability and performance. This configuration is beneficial, especially near the stall, where the inner wing stalls first, keeping the control surfaces functional during critical phases of the flight. However, the unwanted divergent torsional deformation at a low speed, causing the failure of the wing, was considered the main hindrance to the feasibility of this design. The application of aeroelastic tailoring to static aeroelasticity problems, especially the divergence of the swept-forward wing, established the structural viability of the swept-forward laminated composite wing design. Further, the application of aeroelastic tailoring to aircraft performance phenomena like lift and control effectiveness enhancement showed probable applications of aeroelastic tailoring. The future research areas emerged as experimental validation of the findings, the effect of fibre orientation on flutter of forward-swept wings, aeroelastic tailoring of aft-swept wings, easy-to-use and accessible aeroelastic tailoring optimization tools, integration of the aeroelastic tailoring in the design process, and development of smart structures.

2.3. Wing box laminate configuration

Besides swept-forward wing design, an area that attracted aeroelastic tailoring research in the early years was the wing-box

Table 2
Summary of works related to wing box laminate Configuration.

Year	Author(s) [Ref]	Title	Emphasis	Comments
1992	Librescu and Song [13]	On the static aeroelastic tailoring of composite aircraft swept wings modelled as thin-walled beam structures	Thin-wall anisotropic beam structural model with closed cross-sections and transverse shear. The static aeroelasticity response in the sub-critical regime and divergence speeds.Static aeroelastic tailoring of swept aircraft wings made up of advanced composite materials.	The advantage of this study is the employment of a thin-wall beam model with closed cross-sections, which is a better depiction of a wing as compared to classic solid-beam or plate-beam models. The study demonstrated the successful application of aeroelastic tailoring to achieve enhanced divergence speeds for swept aircraft wings made up of advanced composite materials with different sweep angles. The rigid body motion was restrained in the model; the same may be allowed for a more realistic analysis.
1997	Patil [14]	Aeroelastic tailoring of composite box beams	Aeroelastic tailoring using the composite thin-wall box-beam. Theodorsen's aerodynamic model. Flutter and divergence analysis utilizing the V-g method. Validation using the Goland wing. The effect of composite plies lay-up on critical speed values at different wing-sweep values.	The study used more realistic wing modelling with composite thin-wall box-beam like Ref [13] and extended it to dynamic aeroelasticity. Aeroelastic analyses of box-beam configurations with varying levels of bend-twist and extend-twist coupling demonstrated the efficacy of tailoring for modifying the aeroelastic behaviour of a composite wing. The study presented a preliminary flutter analysis only. A detailed flutter analysis including the interaction of different modes could provide a better depiction of the phenomenon and its response to ply orientation variations.

laminate configuration. Lynch and Rogers [12] of General Dynamics studied wing box laminate configuration's aeroelastic tailoring impact, using composite materials, on aircraft performance in 1976. An algorithm was developed to explore wing box laminate configurations of composite materials that satisfy aeroelastic strength criteria. The algorithm was used to explore wing design with aeroelastic objectives and their implications on the performance of the aircraft. The study established the effectiveness of aeroelastic tailoring using anisotropy in laminate layup for improving aeroelastic drag problems, control effectiveness, strength, divergence, and flutter without any weight penalty. The study demonstrated the effectiveness of aeroelastic tailoring for various applications. However, the algorithm is proprietary to General Dynamics, and no details of the algorithm have been shared. The availability of such details could facilitate researchers working in the domain of aeroelastic tailoring.

Table 2 includes a summary of other notable works related to wing box laminate configuration:

2.3.1. Summary and research needs

The analytical methods of the aeroelastic analyses mostly used beam or plate-beam models to approximate the wing structure. The research discussed in Section 2.3 used a thin-walled box-beam configuration to represent the wing structure. It is a much more realistic representation of an actual flexible wing with a hollow structure comprising spars, ribs, etc., covered with a thin skin, as compared to previous studies. Thus, these studies depicted the positive impact of the aeroelastic tailoring phenomenon on aeroelastic drag problems, control effectiveness, strength, divergence, and flutter more convincingly and realistically, paving the path for practical applications. The potential research areas emerged as the effect of fibre orientation on the flutter of swept wings, with detailed flutter analysis including the interaction of different modes and easy-to-use and accessible aeroelastic tailoring optimization tools.

2.4. Miscellaneous contributions

In addition to swept-forward wing design and wing-box laminate configuration, many researchers have explored various

Table 3
Summary of miscellaneous contributions.

Year	Author(s) [Ref]	Title	Emphasis	Comments
1987	Green [16]	Aeroelastic tailoring of aft-swept high-aspect-ratio composite wings	Aeroelastic tailoring application to high-aspect-ratio swept-back wing performance. The integrating matrix method was employed for the aeroelastic solution. The flutter problem was dominant for swept-back wings. The benefits of torsion stiffness were dominant for swept-back wing design, while the bending-torsion coupling that is valuable for swept-forward wing design remained insignificant in this case. Endorsed using laminates with a general or non-symmetric ply orientation.	The focus expanded from static to dynamic aeroelasticity domains and from swept-forward to swept-back wing design. The study ruled out any major disadvantage of using laminates with general or non-symmetric ply orientation, shedding concerns regarding the practical implications of aeroelastic tailoring using an asymmetric laminate design. The study involved a preliminary investigation into the effects of using general laminates with all coupling parameters having non-zero values. Future work could include an in-depth analysis of the effects of using a general laminate with full coupling for aeroelastic tailoring.
1998	Weisshaar, Nam and Batista [17]	Aeroelastic tailoring for improved UAV performance	The use of optimum composite material configuration in tandem with aeroelastic tailoring for improving lateral controllability and range of a novel UAV design. Enhanced swept-wing control-reversal speeds and reduced induced drag for low-aspect-ratio wings (approx. aspect-ratio of 3).	The research provided further results regarding the effectiveness of aeroelastic tailoring for enhancement in performance parameters. The study projected UAV design as the major area for the application of innovative technologies. The proposed research areas included active tailoring through an array of actuators for induced drag and roll control, optimization of the location and size of the active tailoring actuators' array, and coherent static aeroelastic analysis of wings with leading-edge devices for determining the effectiveness and advantages of drag and roll control systems.
2000	Gern and Librescu [18]	Aeroelastic tailoring of composite wings exhibiting nonclassical effects and carrying external stores	Aeroelastic tailoring of composite swept- and straight-wing designs with external stores. A laminated-composite wing plate model with transverse shear but without warping effects. Modelling of stores with inertia and static weights, and aerodynamics based on 3-D strip theory. Solution of the boundary/eigenvalue problem by employing extended Galerkin methods. Study of the changes in the flutter, free vibration, and divergence behaviour with variations of laminate ply orientations and external stores.	The study highlighted the complexity of the relationship, the extent of the variation involved, and the importance of considering the effect of external stores during the preliminary design process for effective flutter identification and the incorporation of requisite aeroelastic tailoring. Future work could include a detailed analysis of different possible external store configurations on the aeroelastic behaviour of a composite wing structure and the challenging task of tailoring to fulfil requirements mandated by different configurations.

applications of aeroelastic tailoring. Amongst those, Rockwell used aeroelastic tailoring to fabricate the wings of a ½ scale remotely piloted research prototype for Highly Manoeuvrable Advanced Technology (HiMAT) aircraft in 1979 [15]. The basic wing shape design was based on the cruise requirements, while aeroelastic tailoring of the wing and canard skins was used to achieve favourable deformation for satisfying the 8-g manoeuvre requirement. The successful flight tests established the positive effect of aeroelastic tailoring. The study demonstrated the use of aeroelastic tailoring to satisfy contradicting requirements for different phases of flight, like the cruise and high-g manoeuvres etc. Accurate knowledge of the material properties was identified as a prerequisite for the correct prediction of the stress and twist distributions. Future work could include precise modelling of the non-linearities in material properties for accurate prediction of the deformation and twist responses of the tailored structures.

Initially, the scope of aeroelastic tailoring was focused on solving the divergence problem of the swept-forward wing design. With a reasonably good amount of work accumulating on the subject and its summary being presented by Shirk et al. [2], researchers undertook studies on various applications of aeroelastic tailoring. Table 3 presents a summary of a few seminal works covering different aspects and applications of aeroelastic tailoring during the last two decades of the 20th century:

2.5. *Discussion and research needs*

An overview of the works covered in Section 2 indicates that, by this time, 'aeroelastic tailoring' had been established as a viable concept. A concrete theoretical basis had been formed, and the application of aeroelastic tailoring to static aeroelasticity problems (especially divergence) had proven the importance of the concept as well as the viability of swept-forward wing design. The accomplishment of various works regarding the aeroelastic tailoring of the forward-swept wing design and ongoing efforts for the development of better structural models of the wing for the tailoring analyses provided foundations for exploring other dimensions of aeroelastic tailoring. Based on the fundamental building blocks of aeroelastic tailoring, researchers ventured into different applications of tailoring ranging from manned to unmanned aerial vehicles, forward-to aft-swept wings, theoretical studies to flight tests, symmetric to asymmetric ply-orientations, passive to active controls, and clean wing configuration to configurations with external stores. Further, the application of aeroelastic tailoring to aircraft performance enhancement (aeroelastic drag problems, control effectiveness, strength, divergence, and flutter) and various phenomena (high-g manoeuvre, high-aspect-ratio swept-back wing design, flutter problem, UAV design, and aircraft design with external stores) demonstrated huge growth potential and opened numerous avenues for the practical applications of aeroelastic tailoring. The future research areas in the domain of aeroelastic tailoring emerged as the experimental validation of different findings, tailoring of swept wings for improvement of flutter behaviour including the interaction of different modes, non-linear modelling, in-depth analysis for using a general laminate with full coupling for tailoring, active tailoring through an array of actuators for induced drag and roll control and the optimization of the actuators' array, coherent static aeroelastic analysis of wings having leading-edge devices, tailoring to fulfil requirements of different possible external store configurations, easy-to-use and accessible aeroelastic tailoring optimization tools, integration of the aeroelastic tailoring in the design process, and development of smart structures.

3. Latest developments and state of the art

With the advent of various state-of-the-art technologies in the twenty-first century, aeroelastic tailoring has significantly benefited from advancements in aerospace materials, aerospace design, and optimization techniques. Research for development in aeroelastic tailoring by incorporating all these technologies is an ongoing process. The details of seminal works in these domains and other state-of-the-art research in the last two decades have been presented in this section.

3.1. *Aeroelastic tailoring optimization*

The growing applications of aeroelastic tailoring highlighted the need for optimization for effective aeroelastic tailoring. The complexity of the composites tailoring problem and the possibility of an almost infinite number of combinations warranted quick, cost-effective, and reliable solutions. Weisshaar and Lee [19] studied the aeroelastic tailoring methodology for joined-wing configuration in 2002. An unusual limitation of this configuration is the risk of body freedom flutter, whereby flutter gets induced owing to the coupling of elastic and rigid body motion modes. The basic aeroelasticity analysis involved the use of the Rayleigh-Ritz method, followed by the use of ASTROS (Automated STRuctural Optimization System) [20] for weight and aeroelastic stability optimization. The analysis identified the position of the centre of gravity as the primary contributor to body freedom flutter. However, it established that weight reduction through aeroelastic tailoring optimization of composite laminates could change the mode of flutter, thereby reducing the sensitivity of flutter to the aircraft's rigid body motion. The outcome of the study manifests the importance of taking rigid body motion into account during structural and aeroelastic optimization. Moreover, it concluded that the joined-wing aircraft configuration could be optimized by aeroelastic tailoring and placing the joining point of the rear wing higher than the front wing's plane, thus eliminating the body freedom flutter. The joined-wing configuration outperforms the conventional wing and tail configuration in terms of lightweight, enhanced stiffness, improved span-efficiency factor, enhanced lift coefficient, reduced drag, and direct side force and lift controllability. However, the risk of body freedom flutter inhibited its employment. The study provided the requisite confidence for using the promising joined-wing configuration in future applications with aeroelastic tailoring and suitable placement of the aircraft wings. However, ASTROS is a multidisciplinary structural optimization procedure developed by Northrop Corporation for the US Air Force that is commercially available against an annual license fee, but its coding details are not available. Future work could include the effect of the placement of cargo, fuel tanks, and other stores on the flutter modes.

Arizono and Isogai [21] studied the supersonic transport cranked arrow wing's aeroelastic tailoring in 2005 and developed a genetic algorithm-based code for its optimization. The developed code was utilised to analyse local buckling and static strength by the finite element method and aeroelastic phenomena by the vibration analysis procedure. All three parameters were set as constraints with weight minimization as the primary objective, and wing box laminate structure optimization was carried out using the genetic algorithm-based code. The cranked arrow wing's preliminary design was optimized using the code. The flow chart of the optimization process is shown in Fig. 2. The optimization solely based on local buckling and static strength requirements did not meet the aeroelastic requirements. Hence, the first optimization was done based on flutter requirements. Subsequently, a laminate structure satisfying all these requirements was achieved. The study demonstrated that the cranked arrow wing's optimization required considering all constraints together or flutter as a primary constraint followed by other constraints. However, the code was developed in-house and was not shared. The availability of the code could facilitate researchers working in the domain of aeroelastic tailoring.

Herencia, Weaver, and Friswell [22] studied the use of aeroelastic tailoring for designing a morphing wing in 2007. Morphing means the wing's passive self-adaptation for performance enhancement when subjected to design flight conditions. The aeroelastic optimization was carried out in two steps, as shown in Fig. 3. Initially, a mathematical program was utilised for the aerodynamic and structural optimization of the wing. Wing box modelling employed anisotropic lamination parameters for skins and spars with standard symmetric ply orientations of ±45, 90, and 0°. Design constraints, including buckling, strength, and in-plane loads, were applied during this phase. The next step involved the use of the genetic algorithm for ply orientation optimization with design and manufacturing constraints. The optimization resulted in about a 1.4% drag reduction, but with an 18.7% weight penalty. The results indicated the applicability of the concept, albeit with room for improvement in optimization speed as well as results. The methodology was restricted to symmetric laminates with standard orientations to facilitate manufacturability, which turned out to be the major limitation for the achievement of the desired objectives. A relaxation of this constraint would have resulted in a much better outcome for the study. The study considers static loading, buckling, and flutter constraints for one flight condition only. The consideration of other flight conditions and the inclusion of divergence, control reversal, and gust constraints in future works may further establish the applicability of the developed methodology to practical problems.

Krüger et al. [23] investigated wing load reduction through passive technologies in 2019. The study presented the employment of aeroelastic tailoring for multi-fidelity wing design using parametric methodology, as shown in Fig. 4. Optimization was performed using two separate models: the shell model and the beam model. The study investigated lamination parameter-based aeroelastic optimization using unbalanced laminates. Two configurations, namely short-range and long-range transport aircraft, were optimized. The optimization with unbalanced laminates resulted in a 10% weight saving as compared to balanced laminates. The process was extended for the inclusion of CFD-based aerodynamic techniques in aeroelastic tailoring. The analysis revealed that aileron effectiveness increases from 0.00 to 0.03 could be achieved with about an 11% increase in weight. The investigation of the impact of tailoring on fatigue was proposed as future work. The study may be extended to include additional load cases for optimization and the integration of control and structural parameters in the sense of active load control.

Othman [24] and Othman et al. [25] presented an uncertainty quantification-based, reliable, and robust multi-level design approach for composite aircraft wing aeroelastic tailoring in 2019. The two-level optimization comprised probabilistic and

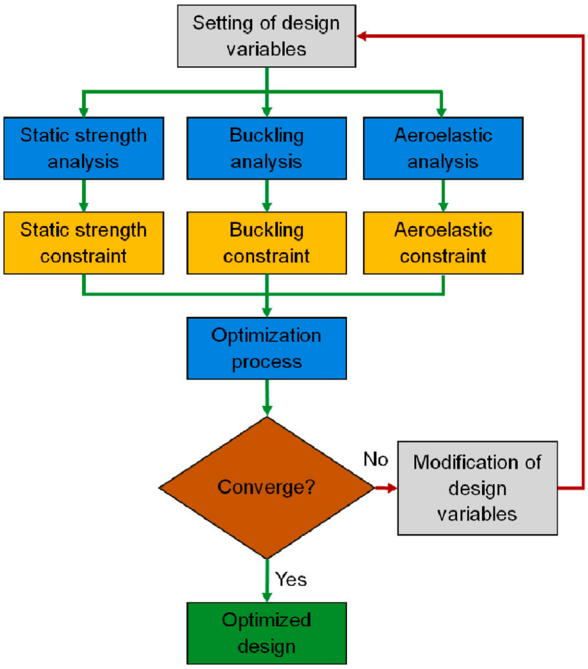


Fig. 2. Flow chart of the optimization process (based on Ref [21]).

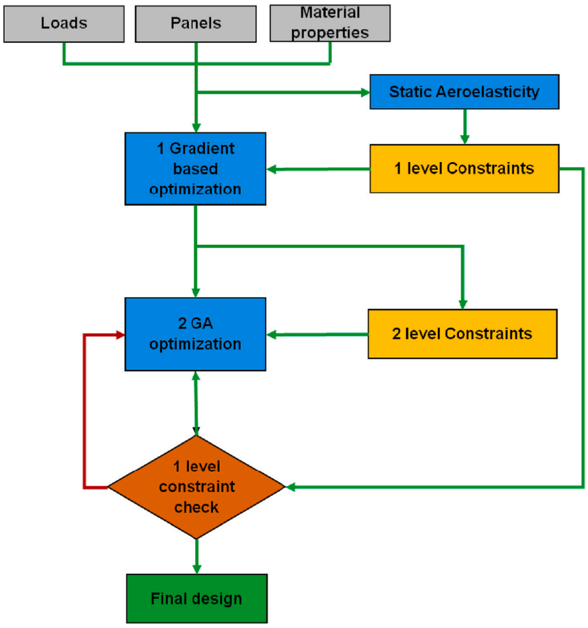


Fig. 3. Flow chart of global optimization (based on Ref [22]).

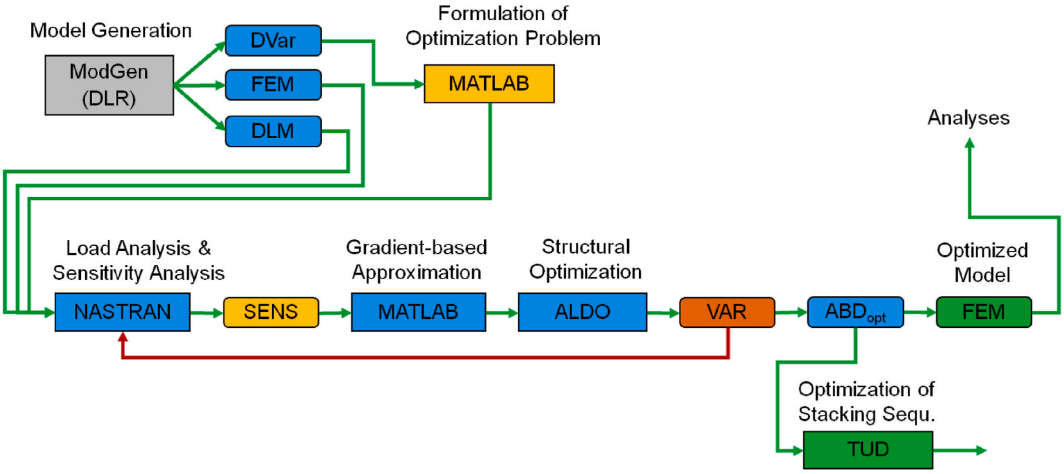


Fig. 4. Aeroelastic tailoring for multi-fidelity wing design (based on Ref. [23]).

deterministic design optimization approaches, as shown in Fig. 5. The study produced a wing design with an optimized weight while considering parametric variations of aeroelastic and structural constraints. The optimized model exhibited the most suitable combination of structural weight minimization with design reliability and robustness. The study involved using a benchmark 'box-like' idealized model for the wing that could economize computational cost for approximating the realistic performance of a wing. The study depicted significant room for economizing the weight (about 32.1% weight reduction) and improving the design using the proposed aeroelastic tailoring approach, with an abundant safety margin against the minimum design and performance certification requirements. The study focused on uncertainties and variations in ply thicknesses and bending and torsional stiffnesses. The same may be extended to predict wing performance variations due to uncertainties in the structural geometry. The combined effect of these uncertainties may also be explored using alternate approaches. Higher-order probabilistic optimization methods may also be employed to analyse the effect of a larger number of randomisation parameters.

A summary of other notable works related to aeroelastic tailoring optimization has been appended to Table 4:

3.1.1. Summary and research needs

Different researchers have made valuable contributions to the optimization of aeroelastic tailoring over the years. The notable approaches include the ASTROS procedure [20], gradient descent-based methods, genetic algorithm-based methods, ZAERO software,

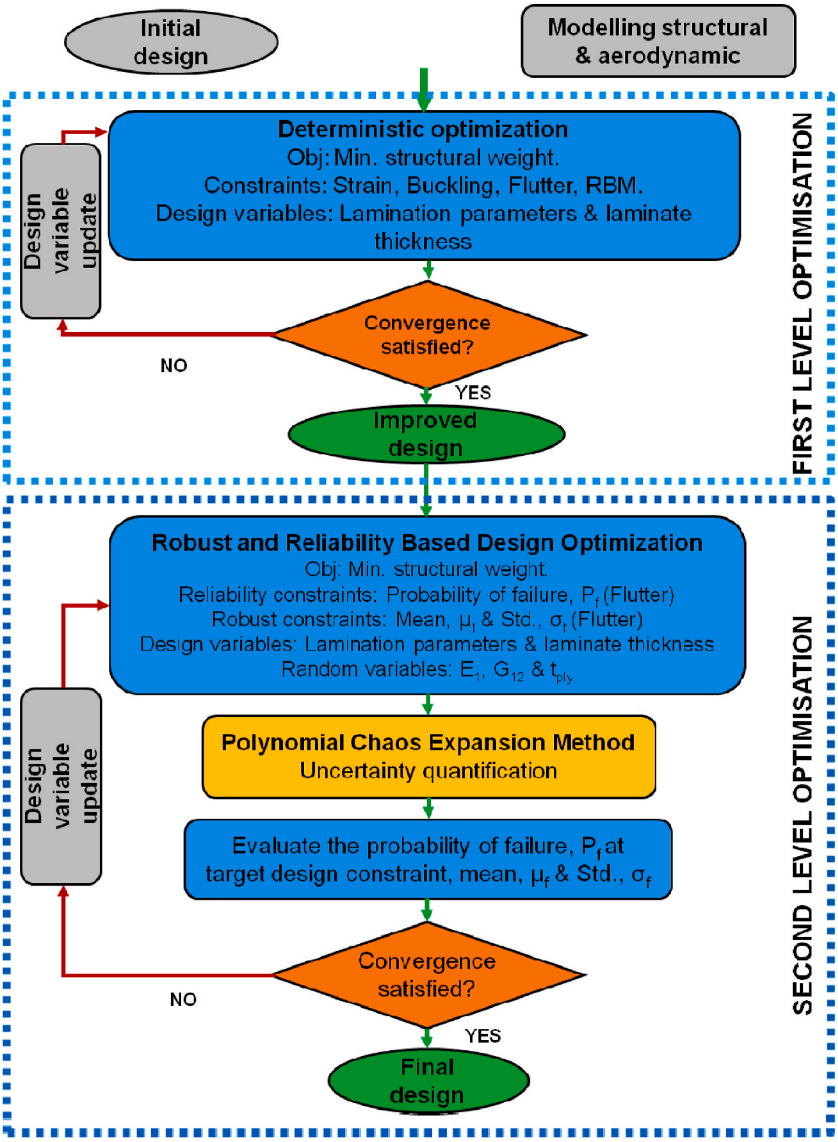


Fig. 5. Multi-level optimization technique (based on Ref [25]).

PROTEUS aeroelastic framework [29], the GCMMA procedure [31], the active aeroelastic wing design approach, shape-function-based methods, surrogate modelling, lamination-parameter-based methods, uncertainty quantification based methods, neural networks, reduced order modelling, differential evolution algorithm, blending constraints method, open-source code GEBTAero [43], BJASCA algorithm [45], optimization framework MACH [46], and various in-house tools/algorithms. These contributions have provided the basis for the solution of many problems. However, the transformation of the research to practical applications requires the inclusion of complex configurations, additional cases, optimization parameters and constraints in the study, and its experimental validation using test cases. Future work could involve the use of better modelling and measurement techniques in combination with higher order, cost-effective and efficient optimization techniques to incorporate the effect of multiple flight conditions and load cases, numerous design variables, randomisation parameters and design/performance/manufacturing constraints to further establish the applicability of the developed methodologies to practical problems, followed by experimental validation.

3.2. *Use of novel material and structural configurations*

The requirement of achieving the desired structural response, for example, bend-twist coupling and flutter and divergence velocities, while optimizing strength and weight using aeroelastic tailoring, warranted a search for novel material and structural configurations that could satisfy these requirements in the best possible manner.

Table 4
Summary of works related to aeroelastic tailoring optimization.

Year	Author(s) [Ref]	Title	Emphasis	Comments
2006	Guo, Cheng, and Cui [26]	Aeroelastic tailoring of composite wing structures by laminate layup optimization	Studied composite wing structure aeroelastic tailoring by optimizing wing-box laminate layup for six different cases. Observed a significant increase in flutter velocity. Identified the contribution of mass distribution associated with taper, taper-ratio, and sweep angle towards aeroelastic tailoring. Flutter optimization using the gradient descent-based and genetic algorithm-based approaches. Bend-twist coupled rigidity CK was found to be the main contributor towards flutter velocity improvement through tailoring for non-tapered un-swept wing-box, while torsional rigidity GJ became the dominant factor for flutter velocity and thus for tailoring of swept and tapered wings.	The study showed that the genetic algorithm-based approach was more suitable for non-tapered, un-swept wings, while the gradient descent-based approach was recommended for swept and tapered wings' flutter optimization. Overall, the study identified the contribution of parameters like mass distribution, taper geometry, and sweep angle to aeroelastic tailoring. It also identified the dominant factors and recommended optimization approaches for different wing geometries. These findings facilitated future researchers in making the right choice of design objectives and optimization algorithms for the case at hand.
2012	De Leon et al. [27]	Aeroelastic tailoring using fiber orientation and topology optimization	Maximizing the natural frequency of vibration modes for flutter velocity enhancement of a laminated composite plate. Aeroelastic stability analyses using the unsteady lift surface methodology ZONA 6 of the software system ZAERO. Calculation of the sensitivity of eigenvalues vis-à-vis design characteristics using analytical methods. There were two optimization approaches. The first involved flutter eigenmode determination, followed by maximization of the eigenvalue. The second involved the calculation of flutter velocity sensitivity to eigenvalues and using the calculated sensitivities to steer the optimization procedure. Weight optimization using ZAERO software with the flutter speed constraint and the design variable of density distribution.	The study was performed using very simple structural and aeroelastic models, with a primary focus on improving fluid-structure interactions instead of the aeroelasticity of the structure. The divergence effects were also not catered for. The procedure is computationally expensive and may not be viable for complex structures. The analysis and optimization tool ZAERO itself is expensive commercial software. Nonetheless, the work showed the importance of optimizing eigenvalues (natural frequencies) in wing structural design and aeroelastic optimization.
2016	Macquart, Werter, and Breuker [28]	Aeroelastic tailoring of blended composite structures using lamination parameters	The use of the lamination parameters as intermediary design variables with blending constraints for aeroelastic tailoring optimization and retrieval of the optimum stacking sequence. Performance evaluation using the PROTEUS [29] aeroelastic framework. The comparison of results obtained through direct transformation from lamination parameters to stacking sequences, and through the incorporation of blending constraints.	The transformation from lamination parameters to stacking sequences often contains errors and discontinuities that require performing several additional steps to make the output sequences useable. The blending constraints approach demonstrated seamless transformation from lamination parameter to stacking sequence domain, producing smooth and realistic output sequences, and thus facilitating the aeroelastic tailoring optimization process. The study provided a basis for using blending constraints for generating stacking sequences with aeroelastic tailoring that could prove vital to future composite tailoring applications.
2016	Werter and Breuker [30]	A novel dynamic aeroelastic framework for aeroelastic tailoring and structural optimization	A dynamic structural design and aeroelastic tailoring optimization methodology utilizing the Globally Convergent Method of Moving Asymptotes (GCMMA) [31]. Span-wise discretized wing model comprising numerous sections, with every section containing multiple	The analyses did not consider constraints like control reversal, performance, and buckling. However, the study demonstrated the usefulness of the developed design methodology as well as the superior results for optimization with aeroelastic tailoring. The GCMMA is a specialized procedure for

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Table 4 (*continued*)

Year	Author(s) [Ref]	Title	Emphasis	Comments
			laminate layers having different thicknesses and stiffnesses. An unsteady aerodynamic state space model was coupled to a linearized model of a geometrically non-linear beam to capture the dynamic aeroelastic behaviour. Optimization for an isotropic and a tailored wing subjected to manoeuvre loading conditions under aerodynamic, aeroelastic, and structural constraints.	the optimization of large-scale, multiple-variable problems, particularly targeting topology and structural design optimizations. The inclusion of buckling, control reversal, gust, performance, and transonic aerodynamic constraints in future works may further establish the applicability of the designed approach to practical problems.
2017	Alyanak and Pendleton [32]	Aeroelastic tailoring and active aeroelastic wing impact on a lambda wing configuration	Two approaches were used for the supersonic lambda wing's aeroelastic tailoring optimization: the first was the Active Aeroelastic Wing (AAW) design approach employing ZAERO in combination with NASTRAN, and the other was the standard NASTRAN approach. Eight variants of a finite element model for studying wing stiffness variation. The AAW design approach involved simultaneous structural and control sizing processes compared to NASTRAN's traditional flutter constraint-based aeroelastic sizing. Optimization of all variants using both approaches. The results' assessment was based on control-surface effectiveness and weight reduction.	The best results for lambda wing configuration were obtained for the case involving maximum freedom in choosing primary axis orientation and material distribution, using aeroelastic tailoring with the AAW approach. The iterative use of two software programs for AAW optimization is a cumbersome process with slow convergence and multiple intermediary solutions. The primary outcome of AAW is a highly flexible design with very little or adverse control-surface effectiveness, and additional steps are required to maintain the desired aircraft manoeuvrability. The economic viability of commercial software (ZAERO) is also a point of concern. However, the study established the need for a proper industrial-standard AAW approach.
2017	Qian, Zeng, and Park [33]	Aeroelastic tailoring of the composite wing structure via shape function approach	A shape-function-based method for composite wing structure's aeroelastic tailoring optimization. A smooth wing spar/skin thickness distribution was obtained through the superposition method by setting bi-linear Lagrange's shape function coefficients as design variables. Aeroelastic optimization for various flutter constraints and shape function settings.	The thickness distribution achieved by running a structural optimization solution followed by the superposition of shape functions was quite smooth as compared with the element-based approach, which can also result in an uneven wing spar/skin thickness distribution. Thus, the analyses established the efficacy of a shape-function-based approach for solving structural sizing problems.
2018	Meddaikar et al. [34]	FLEXOP–Application of aeroelastic tailoring to a flying demonstrator wing	The flying demonstrator wing design for a UAV using aeroelastic tailoring under the Flutter Free Flight Envelope eXpansion for ecOnomical Performance improvement (FLEXOP) program. The use of aeroelastic tailoring for passive load reduction. Optimization using a tool jointly developed by the DLR Institute of Aeroelasticity and Delft University of Technology (DUT). Analyses used two wings: the first with conventional symmetric and balanced laminate design and the second with unbalanced and aeroelastically tailored laminates to incorporate the requisite bend-torsion coupling. An 8% reduction in weight and up to 6% decrease in wing root bending moment for an optimized aeroelastically tailored wing vis-à-vis the conventional wing. Manufacturing and testing to validate and update the simulation model. The testing verified sustenance of 5 g and -2 g limit load conditions.	The study has been validated through static testing. The dynamic behaviour may be validated through ground vibration testing and may be followed by control updating and flight testing. The future outcome of the study could be the development of a full-scale wing for commercial aircraft. However, the data is proprietary, and details are not available.

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Table 4 (*continued*)

Year	Author(s) [Ref]	Title	Emphasis	Comments
2018	Rajpal et al. [35]	Including aeroelastic tailoring in the conceptual design process of a composite strut braced wing	A multi-disciplinary design analysis of strut-braced aircraft. Surrogate modelling used the wing plan-form characteristics as design parameters to integrate aeroelastic tailoring during the conceptual design phase. An AGILE [36] concept-based technique for optimization of the surrogate model employing PROTEUS [29] with fuel mass reduction as the optimization objective. The comparison of results with direct structural optimization by employing PROTEUS indicated room for improvement in the surrogate model.	The study proposed the use of surrogate modelling to integrate aeroelastic tailoring during the conceptual design phase. This may facilitate the structural engineers' objective of incorporating maximum design requirements during the initial design phase and making minimum changes at later stages. However, the approach needs a lot of refinement before being put into practice, as indicated by the results of the study. Increasing the sample size and employing better curve-fitting techniques could improve the accuracy of the surrogate model.
2018	Kirsch et al. [37]	Assessment of aeroelastic tailoring effect on high-aspect-ratio composite wing flutter speed using an open source reduced order model solver	An optimized open-source Python and Fortran-based reduced-order model solver for studying flutter velocity enhancement of composite wings with high-aspect-ratios employing aeroelastic tailoring. The validation of the model and solver against the Goland [38] and Patil [39] wings.	The study demonstrated the complexity of the aeroelastic tailoring problem and the requirement of an optimization process through the simulation of a simplistic laminate configuration. The application of the model and solver to complex configurations with the employment of a suitable optimization technique may be explored to ascertain its suitability for practical purposes.
2019	Rongrong et al. [40]	Composite material structure optimization design and aeroelastic analysis on forward swept wing	Aeroelastic tailoring optimization of the forward-swept wing to address the problem of torsional divergence. Optimization using MATLAB's Genetic Algorithm (GA) in combination with Radial-Basis-Function-Neural-Networks (RBFNNs). Significant reduction in displacement (about 70% for the worst-case scenario around Mach 1.0) and increase in first and second modal frequencies.	A lot of work has already been done in the late twentieth century regarding the aeroelastic tailoring of the forward-swept wing to address its divergence problem (Section 2.2). The current work focuses on the employment of the latest optimization approaches for the solution of the same problem. The results demonstrated that the proposed optimization framework could be employed for effective aeroelastic tailoring of the forward-swept wing.
2019	Sanches, Guimarães, and Marques [41]	Aeroelastic tailoring of nonlinear typical section using the method of multiple scales to predict post-flutter stable LCOs	Typical section's aeroelastic tailoring optimization with pitch stiffness non-linear hardening for expanding flutter boundary and minimizing post-flutter Limit Cycle Oscillation (LCO) amplitude. The reduced-order modelling with the method of multiple scales for quick evaluation of results. Aeroelastic tailoring using a differential evolution algorithm.	The study aimed to find a configuration whereby aeroelastic tailoring could not only enhance flutter speeds but also enable the wing to stabilize with minimum post-flutter LCO amplitudes after encountering the flutter threshold and going beyond it. The optimization results depicted the possibility of designing aeroelastic tailoring solutions for flutter velocity enhancement with the minimization of post-flutter LCOs. The results of the study could affect future design requirements.
2020	Bordogna et al. [42]	Static and dynamic aeroelastic tailoring with composite blending and manoeuvre load alleviation	The regional aircraft wing's composite stacking sequence was finalized with optimal design by employing blending constraints. Optimized load conditions and the role of manoeuvre load mitigation techniques in weight reduction.	The study revealed that manoeuvre load alleviation resulted in a 5–6% weight reduction. The blending constraints did not contribute to weight reduction but facilitated the design finalization and subsequent manufacturability of the structure. The analyses also benefitted from these constraints in terms of the reduced number of element failures. Thus, the proposed methodology could be used for realistic design optimizations.
2020	Kirsch et al. [43]	Tightly coupled aeroelastic model implementation dedicated to fast aeroelastic tailoring optimization of high aspect ratio composite wing	Developed the open-source code GEBTAero for evaluating the impact of aeroelastic tailoring optimization on extremely flexible aircraft's critical velocities. A homogenization tool and an unsteady, induced-flow, finite-state aerodynamics	The results demonstrated a strong relationship between critical aeroelastic velocities and bend-twist coupling of composite structures with unbalanced laminates. The study further depicted the high dependency of aeroelastic behaviour on

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Table 4 (*continued*)

Year	Author(s) [Ref]	Title	Emphasis	Comments
			model tightly coupled with Geometrically Exact Theory (GEBT). Implementation of the optimized code in Fortran with special emphasis on computational time. Aeroelastic tailoring of a simplistic two-ply composite laminate configuration and an anisotropic composite wing having high-aspect-ratios. The relation between critical aeroelastic velocities and bend-twist coupling.	laminates' ply orientations. The application of the model and solver to an anisotropic wing with the development of an efficient optimization code has illustrated the suitability of the proposed methodology for handling complex configurations. Validation of the findings through wind tunnel testing could further establish the applicability of the proposed methodology to real-life problems.
2022	Kruger et al. [44]	Application of Aeroelastic Tailoring for Load Alleviation on a Flying Demonstrator Wing	Extension of the work of Meddaikar et al. [34]. The wing-box design optimization used the DUT-DLR joint methodology. There were two wing designs: one tailored with unbalanced laminates for producing the required bend-torsion and shear-extension coupling, and the other with symmetric, balanced laminates for reference. The numerical optimization, manufacturing, and testing of both designs for validation and improvement of corresponding simulation models. There was about an 8% weight reduction for the tailored wing as compared to the reference wing. Validation through design, manufacture, and flight tests of a UAV.	The completion of the design, optimization, manufacture, and test cycle and the flight testing results further validated the aeroelastic tailoring methodology proposed in Ref. [34]. However, the scatter in the simulation and the flight-testing data suggest further refinement in the FE models and the flight data measurement systems. The work is highly promising and may be used to develop fully operational UAVs. Another outcome of the study could be the development of a full-scale wing for commercial aircraft.
2022	Li et al. [45]	Aeroelastic tailoring of composite rudder skin considering variable angle tow laminates by a hybrid backtracking search-JAYA-Sine Cosine Algorithm	Used the novel algorithm BJASCA, which is a combination of the JAYA algorithm, the sine-cosine algorithm, and backtracking-search algorithms. Aeroelastic tailoring optimization for critical flutter velocity enhancement while maintaining lightweight structure and constant skin thickness. There was about a 76.4% increase in the critical flutter velocity for optimized structures compared to non-optimized structures.	The superior performance of the algorithm for finding the global optimum may facilitate the solution of the aeroelastic tailoring optimization problem. The validation of the proposed solution through experimental testing could facilitate ascertaining its suitability for practical purposes.
2022	Mangano et al. [46]	Towards Passive Aeroelastic Tailoring of Large Wind Turbines Using High-Fidelity Multidisciplinary Design Optimization	Use of aero-structural optimization framework MACH for torque maximization and mass minimization. Two-step optimization: first a loosely coupled aero-structural model, followed by a tightly coupled model. Approx. 19.4% mass reduction and 9.9% torque enhancement with equal weights assigned to both objectives.	The envisaged advantage of this approach is the reduction of design iterations at later stages, thereby producing lightweight and cost-efficient rotors. The study considered design variables of twist distribution and panel thickness with only one steady-state flow case. The work could include different flow conditions and a larger number of design variables to simulate more realistic and complex problems.

3.2.1. Novel material configurations

One of the material configurations that emerged as a promising candidate for aeroelastic tailoring is curvilinear fibre and tow-steered composite materials. Haddadpour and Zamani [47] analysed composite wing's aeroelastic optimization using curvilinear fibre in 2012. The wing was modelled as a thin-wall beam for investigating curvilinear fibre's effect on the wing's aeroelastic behaviour. Non-classical phenomena like non-uniform torsion, rotary inertia, warping constraint, and transverse shear were also considered along with Wagner function aerodynamic loads during structural model development. The span-wise changes in curvilinear fibre alignment provide varying structural stiffness along the span, which optimizes the aeroelastic instability (flutter) speeds, taking the manufacturing constraints into account. The improvement has been verified by comparing the varying structural stiffness wing with the typical uniform structural stiffness wing through numerical simulations. The study established the superiority of curvilinear fibre over conventional fibre for aeroelastic optimization. Thus, it provided the basis for further research on the use of this type of composite materials for the aeroelastic tailoring of aircraft structures.

Wang and Peeters [48] studied the aeroelastic optimization of a tow-steered composite wing subjected to gust loading conditions and cruise shape constraints while ensuring its manufacturability in 2021. The proposed methodology involved using the aeroelastic tailoring framework PROTEUS developed by Werter and Breuker [29] for tow-steered composite wing structure's conceptual design by adding a layup extraction step (Fig. 6). The proposed framework took cruise shape and manufacturability constraints along with dynamic and static loading conditions into account and performed aeroelastic tailoring and layup extraction sequentially and iteratively. Initially, wing sections' thickness and lamination parameters were optimized with gust and manoeuvre loads utilizing PROTEUS. Jig twist distribution was then optimized to achieve a specified cruise shape for optimum aircraft cruise performance. Subsequently, the stacking sequence was extracted with minimal steer radius constraint. The constraints were verified and made stricter to cater for lamination parameters' accuracy loss during the extraction step. The initial step was iterated till the satisfaction of constraints in entirety post fibre orientation extraction. The suggested optimization framework was checked by investigating the impact of gust loading conditions and cruise shape constraints on aeroelastic tailoring during NASA Common Research Model (CRM) Wing design. A refined version of the same work was later presented by Wang, Peeters and De Breuker [49] in 2022. The optimization results showed potential for weight reduction through the inclusion of jig twist optimization and cruise shape constraints. It was observed that wing optimized using solely static loading conditions could fail when subjected to gust loading conditions, whereas wing optimization using only gust load resulted in weight penalty vis-à-vis static tailoring case. The results showed the need to consider cruise shape constraints and gust loading conditions in tandem for optimization, thus establishing the relevance and significance of the recommended optimization framework. The study considered weight reduction with cruise shape constraints and gust loading conditions only. The addition of divergence, flutter, buckling, and buffeting constraints could allow the development of more practical solutions. Nonetheless, the study is a valuable contribution towards research on tow-steered composites and their subsequent employment in practical applications.

Table 5 contains a summary of other seminal works related to curvilinear fibre and tow-steered composite materials:

3.2.1.1. Summary and research needs. The tow-steered composite materials exhibit a change in fibre orientations along the lay-up path. It offers an enhanced design freedom that outperforms the conventional unidirectional composites in terms of design optimization. This advantage has been successfully utilised by researchers in aeroelastic tailoring for the performance enhancement of composite wings in terms of gust load, divergence, and flutter velocities. Various optimization tools like MATLAB genetic algorithms and codes, NASTRAN software, GCMMA [31], matrix perturbation theory, and PROTEUS [29] were also used in the process. Despite the employment of superior modelling techniques for successful demonstration of the superior performance of the tow-steered

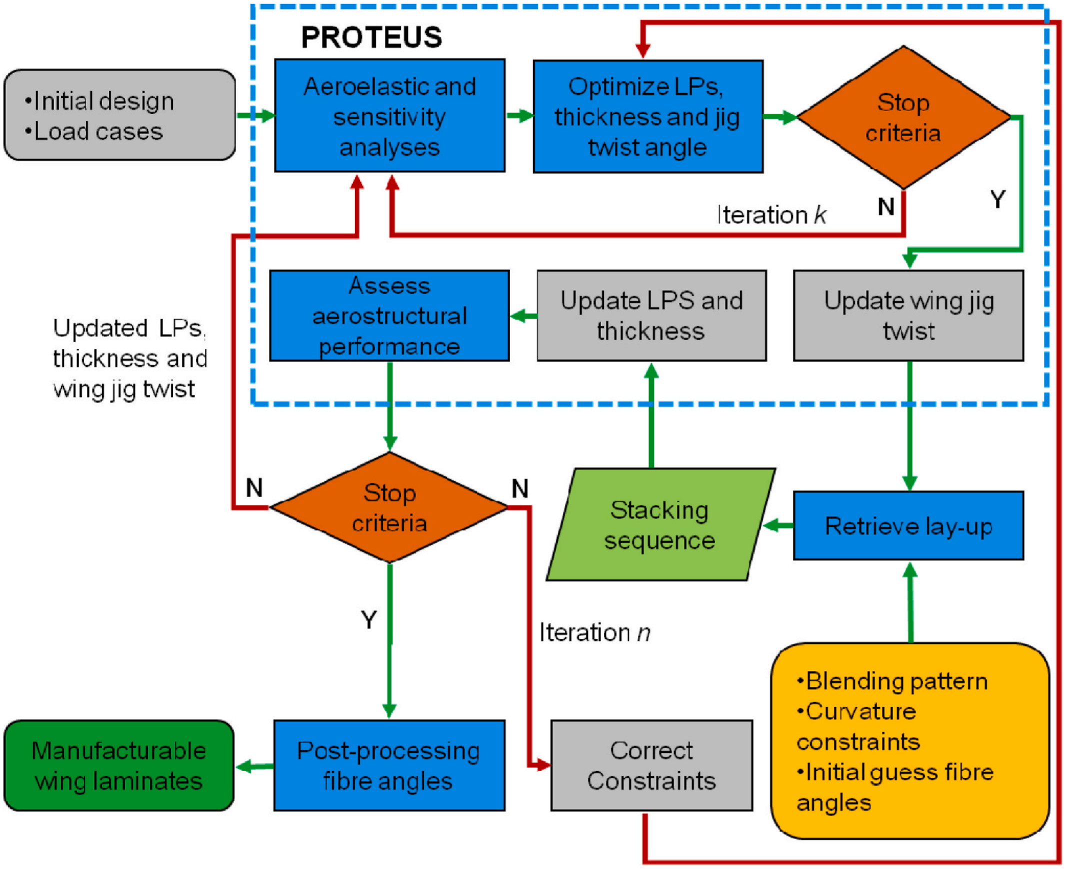

Fig. 6. An aeroelastic optimization framework for tow-steered composites (based on Ref [48]).

Table 5
Summary of works related to curvilinear fibre and tow-steered composite materials.

Year	Author(s) [Ref]	Title	Emphasis	Comments
2013	Stodieck et al. [50]	Improved aeroelastic tailoring using tow-steered composites	Tow-steered composite materials employment to improve aeroelastic tailoring methodology. The uniform cross-section un-swept composite wing was modelled as a 1-D beam using the Rayleigh-Ritz method. The customized aerodynamic strip theory was used. A symmetric laminate layup with span-wise variation in the orientation of outer fibre layers. Aeroelastic analysis in MATLAB. Verification using NASTRAN. The impact of fibre orientation variation on gust load, divergence and flutter velocities, flexural axes, and free vibration.	The analyses demonstrated both positive and negative impacts of employing tow-steered composites on the aeroelastic behaviour of the wing. The study showed that tow-steered laminated composites expanded room for design, allowing the incorporation of better design methodologies vis-à-vis conventional one-directional laminated composite material. Thus, it established superior aeroelastic tailoring performance of tow-steered laminates over traditional unidirectional ones. The study employed a simplified 1-D beam model. A more realistic model could provide better results to facilitate designers in implementing the proposed methodology for practical applications.
2015	Stodieck et al. [51]	Optimization of tow-steered composite wing laminates for aeroelastic tailoring	Aeroelastic tailoring of the simple 2-D wing using tow-steered composite materials. The beam model was modified from Ref. [50] with the aeroelastic model being the same as Ref [50]. A symmetric laminate layup with span and chord-wise variation in fibre orientation. Ply-orientation optimization using MATLAB genetic algorithm. Multi-objective optimization using a simple normalized objective function weighting scheme. Up to 52% reduction in peak gust loads and a 13% increase in divergence/flutter velocities vis-à-vis the optimized straight fibre laminates.	The study demonstrated that optimization involving variation of fibre orientation in each layer irrespective of other layers was superior as compared to optimization based on rotation of standard span-wise ply orientations. The use of a 3-D model of a realistic wing, followed by experimental testing, could further establish the viability of the proposed methodology for practical applications.
2017	Stodieck et al. [52]	Aeroelastic tailoring of a representative wing box using tow-steered composites	NASA CRM-based 3-D FE modelling and analysis using MSC NASTRAN. DLM-based aerodynamics in NASTRAN. Optimization using GCMMA [31] with the design variables of 1-D and 2-D rotation angle and laminate thickness. Weight optimization with buckling loads and strains inflicted by dynamic gust and manoeuvre loads, control effectiveness, flutter stability and 1-g flight condition as constraints.	The study established better effectiveness of tow-steered laminated composites for weight optimization as compared to conventional straight fibre materials. However, the washout phenomenon associated with the maximum weight reduction configuration resulted in reduced effectiveness of aileron control. This warrants a balance in control effectiveness and weight reduction. Further, the study could include different flight conditions and a larger number of design variables e.g., laminate ply percentages, and stringer/spar thicknesses to simulate more complex problems, followed by experimental testing for validation. Future works could also investigate the tailoring of geometrically non-linear, and highly flexible wing designs.
2020	Zhang, Chen and Zu [53]	Aeroelastic tailoring method of tow-steered composite wing using matrix perturbation theory	The study of the impact of tow steering fibre angle on aeroelastic behaviour. Modelling and aeroelastic analysis in MSC NASTRAN using multi-layer composite shell element. The use of matrix perturbation theory to determine the region with high sensitivity of the flutter speed to local fibre orientation. Increasing the flutter speed by adjusting the fibre angle in the high-sensitivity region only. The optimization for curved and straight fibre laminate plate wing models using a conventional genetic algorithm, and for curved fibre using matrix perturbation theory. The results revealed similar flutter velocity enhancement (about 42.96%) for curved fibre using genetic algorithm and matrix perturbation theory.	The study demonstrated the superiority of the developed technique as it required the fibre angle orientation adjustment in a small region and that too without iterative calculations, thus reducing the computational as well as manufacturing costs involved in the process. The study also showed that it was possible to further reduce the already minimized curvature angle by expanding the tailoring region. This would make the curvature less and smoother, thus paving the way for an effortless and flawless manufacturing process. The study provided a valuable tool to facilitate the designers for the quick and efficient tailoring of the wing to produce easy-to-manufacture design configurations. The data is not available; however, it appears from the discussion and results that the study considered a single flight configuration.

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Table 5 (*continued*)

Year	Author(s) [Ref]	Title	Emphasis	Comments
				Therefore, the study could include different flight conditions and a larger number of design constraints like buckling and gust loads etc to simulate more complex problems, followed by experimental testing for validation.
2022	Tatar et al. [54]	Aeroelastic tailoring optimization of a combat aircraft wing with tow-steered composites	Employing aeroelastically tailored one-dimensional and two-dimensional variable angle tow-steered and unidirectional composites for maximizing the performance of a combat aircraft wing. MATLAB-based optimization code with NASTRAN algorithms for weight optimization with aeroelastic and structural constraints by optimizing ply angles and thickness distributions. Both one-dimensional and two-dimensional tow-steered configurations showed better weight savings than unidirectional laminate configurations, with a maximum of about 35% weight saving for two-dimensional variable angle tow-steering.	This work demonstrated the superiority of employing one-dimensional and two-dimensional variable angle tow-steered composites for aeroelastic tailoring. The study considered weight reduction with buckling, twist, stress, strain, and manufacturing constraints. The addition of divergence, flutter, and buffeting constraints, followed by experimental testing, could further establish the viability of the proposed methodology for practical applications.

composite materials, the other challenges and research needs are similar to the ones identified in Section 3.1.1 i.e., inclusion of complex realistic scenarios, and quick/robust/cost-effective optimization, followed by experimental validation. The employment of tow-steered composites for the manufacturing of actual aviation structures could also be prohibited by the lack of certification requirements for these novel laminate configurations and the industrialists' concern for establishing a facility with limited applications, say wing only. The availability of certification standards and confidence-building measures are, therefore, additional prerequisites for practical applications.

3.2.2. *Novel structural configurations*

In addition to novel material configurations, the quest for better aircraft performance with weight minimization brought the aeroelastic researchers to the realm of novel structural configurations. The most prominent configurations that caught the eye of aeroelastic tailoring researchers include spar/rib/stringer orientations and planform geometries, selectively reinforced structures, and additively manufactured lattice structures. Francois, Cooper and Weaver [55] experimentally investigated the use of spar/rib orientations for aeroelastic tailoring in 2015. The variation in the un-swept, uniform cross-section wing's aeroelastic performance vis-à-vis different rib and spar configurations was analysed. The investigation involved experimental testing employing 3-D printed wing structures and numerical simulations. The dynamic and static testing established a considerable effect of rib and spar configurations on aeroelastic and structural properties. There was a considerable difference between the experimental and simulation results; however, both approaches demonstrated that rib orientation changes caused modification in bend-twist coupling (associated with flexural axis location), static and aeroelastic structural responses, and natural frequencies of the wings. The study could try to reduce gaps between experimental and simulation results by improving the FE models, manufacturing processes, and testing of the wing to ascertain the physical wing properties with accuracy.

Table 6 presents a summary of the notable works related to novel structural configurations:

3.2.2.1. Summary and research needs. The aeroelastic tailoring using different structural configurations including variation of spar/rib/stringer orientations and planform geometries, selectively reinforced structures, and additively manufactured lattice structures has been investigated by researchers. The studies have demonstrated the positive impact of the wing internal structure variations on bending rigidity, torsional rigidity, bend-twist coupling, static structural responses, divergence/flutter velocities, gust response, and natural frequencies of the wings; the stiffened laminate composite panels on flutter mechanisms; and additively manufactured lattice structures for flutter optimization. The optimization methods including IPOPT optimizer [59] and physics-based lower-order modelling have been used. The concept of using stiffened laminate panels is in the initial stages, but the works on internal structural configuration and additively manufactured lattice structures have highlighted the extensive design freedom and the associated advantages offered by these techniques. However, the same freedom also poses the challenge of optimizing the innumerable possible combinations that exist in the vast design space. The researchers need to find the optimum solutions considering all types of constraints and design combinations, which requires the ultimate cost-effective and efficient modelling/optimization techniques, followed by experimental validation and certification of the optimized structures through regulatory bodies/relevant standards.

3.2.3. *Novel material and structural configurations*

Other than discrete works in the domains of novel material and structural configurations, some researchers have ventured into both domains. A summary of a few seminal works has been presented in Table 7:

Table 6

Summary of works related to novel structural Configurations.

Year	Author(s) [Ref]	Title	Emphasis	Comments
2017	Francois, Cooper and Weaver [56]	Aeroelastic tailoring using the spars and stringers planform geometry	Aeroelastic tailoring utilizing stringer/spar chord-wise locations and shape. Divergence and flutter velocities, gust response, deformation response to aerodynamic loads with static tip load, and natural vibration mode frequencies. No significant effect of stringer planform geometry variation on wing loads and deformations. The optimization of spar planform geometry resulted in a 25% increase in flutter velocity and a more than 10% decrease in bending moment at the root for gust loads. The study showed that spar planform geometry variation effects were like wing sweep variations for static loads, while these were more pronounced than wing sweep effects for dynamic loading conditions.	The analyses established that spar sweep angle changes affected the wing's bending rigidity along with bend-twist coupling, while spar chord-wise location and geometry affected the wing's torsional rigidity along with bend-twist coupling. The study involved unconstrained weight reduction and tip load/twist, natural frequency, aeroelastic instability speeds, and gust response optimization with hard constraints enforced on structural viability. Performing a constrained optimization with the addition of buckling, stress, strain, and buffeting constraints in addition to the above-mentioned objectives, followed by experimental testing, could further establish the viability of the proposed methodology for practical applications.
2017	Marques, Natarajan and Ferreira [57]	Evolutionary-based aeroelastic tailoring of stiffened laminate composite panels in supersonic flow regime	The super-sonic flutter performance improvement of laminated composite panel(s) reinforced by attaching stiffener(s) through aeroelastic tailoring. The optimization by maximizing dynamic pressure for critical flutter conditions through a genetic algorithm. Impact of boundary conditions.	The analysis demonstrated that suitable stiffening achieved through tailoring could elevate the flutter limits and alter flutter mechanisms, subject to adequately constrained boundaries. The study is purely theoretical and simulated the attachment of stiffeners with an arbitrary stiffness elastic foundation or a simply supported boundary condition. The inclusion of more realistic stiffener modelling techniques and analyses with various structural and aeroelastic constraints could provide better insight into the phenomenon. However, the study provides a basis for investigating the employment of laminated composite panels reinforced by attaching stiffeners for aeroelastic tailoring.
2018	Opgenoord and Willcox [58]	Aeroelastic tailoring using additively manufactured lattice structures	Employment of the additively manufactured lattice structures for the construction of a wing with aeroelastic stability constraints. Flutter optimization employing Interior Point OPTimizer (IPOPT) [59]. A transonic-flutter model coupled with low-order structural dynamics formulation. A 3% enhancement in flutter velocity with only about a 3.5% weight increase from the minimum weight achieved without aeroelastic stability constraints.	The extensive design freedom offered by lattice structures along with their higher specific stiffness could be useful for aeroelastically tailored aerospace structures. The study is very preliminary; however, it provided a basis for further research on the use of additively manufactured lattice structures for the construction of aircraft structural parts with aeroelastic tailoring.
2018, 2019	Opgenoord [60], Opgenoord and Willcox [61]	Transonic flutter prediction and aeroelastic tailoring for next-generation transport aircraft [60]. Design methodology for aeroelastic tailoring of additively manufactured lattice structures using low-order methods [61].	A continuation of Ref [58]. Flutter prediction in the transonic regime using physics-based lower-order modelling for reducing computational costs, and its avoidance using aeroelastic tailoring. Optimization for flutter enhancement and weight minimization. An 80% weight reduction by redesigning a solid aircraft bracket in a case study. A 15% boost in flutter speed with only about a 1.8% weight increase from the minimum value achieved for the wing without aeroelastic stability constraints.	The extensive design freedom offered by lattice structures allowed aeroelastic tailoring of the wing's internal structure for flutter velocity enhancement with negligible weight addition, establishing the usefulness of these structures. The study considered weight reduction with buckling, stress, flutter, and manufacturing constraints. The addition of divergence and buffeting constraints, followed by experimental testing, could further establish the viability of the proposed methodology for practical applications.

3.2.3.1. *Novel material and structural configurations.*

The researchers explored the use of curvilinear stringer/spar/rib configurations, thickness distributions, functionally graded materials, and tow-steered laminated composites for aeroelastic tailoring to improve static wing stress, flutter velocity, weight, and fuel consumption. However, all the case studies examined the effect of different design variables under different constraints/objectives. The through-thickness topology optimization was also studied, but it is still a work in progress. The challenges and research needs remain the same as discussed in Sections 3.2.1.1 and 3.2.2.1 i.e., finding the optimum configuration considering all types of constraints and design combinations using the most efficient and cost-effective modelling/optimization techniques, experimental validation and certification of the optimized structural/material configurations through regulatory bodies/relevant standards.

3.3. *Miscellaneous contributions*

In addition to the categories discussed above, many researchers explored various state-of-the-art technologies and applications of aeroelastic tailoring. A summary of a few seminal works is depicted in Table 8, and the aeroelastic tailoring process of a next-generation tilt-rotor presented by Marano et al. [64] is shown in Fig. 7:

Table 7
Summary of works related to novel material and structural Configurations.

Year	Author (s) [Ref]	Title	Emphasis	Comments
2014	Jutte et al. [62]	Aeroelastic tailoring of the NASA common research model via novel material and structural configurations	Employment of the NASA CRM to investigate the use of new structural and material configurations for aeroelastic tailoring. The use of curvilinear stringer/spar/rib configurations, thickness distributions, functionally graded materials, and tow-steered laminated composites. Aeroelastic framework comprising MATLAB, NASTRAN, and PATRAN. Static aeroelastic stress, dynamic flutter onset, and wing weight. The use of tow-steered composites for wing skin exhibited a 47% reduction in static wing stress with a 14% weight reduction and a 3.5% weight reduction with a 100% improvement in flutter velocity. The graded materials exhibited no advantage for the wing skin; however, the use of graded materials in ribs and spars gave a 3.2% and a 4.8% flutter velocity enhancement without any stress or weight penalty for grading in material as well as thickness. The structural member configuration changes gave a significant reduction in weight for inner spar removal, with adjustment in stringer positions and the use of curvilinear ribs to maintain performance. The best results involved a 13.9% flutter velocity enhancement and a 5.6% reduction in weight for a 3% stress penalty, which was superior to the flutter velocity enhancement achieved by employing conventional rotated ribs with identical weight in terms of flutter speed as well as stress value.	The study laid a foundation for future optimization scenarios involving the discussed technology domains. However, all three studies disjointly explored the effect of tailoring on static aeroelastic stress, flutter onset, and weight without proper optimization tools and constraints. Moreover, the design-space exploration strategies were different for different techniques, making the fidelity level difficult to compare. Each tailoring strategy warrants detailed investigation and optimization with the inclusion of buckling, strains, divergence, buffeting, and manufacturing constraints and the utilization of the proper tools. Further, the combination of different technologies e.g., tow-steering for skin in conjunction with structural member configurations and graded materials for internal structures may be employed to minimize weight and maximize performance. The optimization tools also need upgradation to manage the vast design space and the substantial number of variables associated with this task. Subsequently, the complete aircraft structure including engines and external stores also needs to be considered. The experimental testing and validation of the wing structures optimized using the best technology or the combination of technologies would then pave the way for their practical utilization.
2020	Smith et al. [63]	Passive Aeroelastic Tailoring	Passive aeroelastic tailoring by two distinct approaches: the first is tow steering, and the other is using novel wing structures with through-thickness topology optimization. Tow steering of the NASA CRM allowed a reduction of up to 24% and 2.3% in weight and fuel burn, respectively. The development of novel advanced tools for the challenging task of 3-D topology optimization. The solution of a few extraordinarily complex and large design space problems involving frequency and stress constraints.	The tow-steering optimization considers weight reduction and fuel-burn objectives only. The addition of flutter, gust, and buffeting constraints would allow the development of more practical solutions. Nonetheless, the study provides a gateway for further research on tow-steered composites and their subsequent employment in practical applications. The vast design space involved in the parameterization of topology throughout wing thickness presented numerous technical challenges. The task of optimizing through-thickness topology is still a work in progress, but the study demonstrated an implementable approach for the achievement of the desired objectives.

Table 8
Summary of miscellaneous contributions.

Year	Author(s) [Ref]	Title	Emphasis	Comments
2014	Jutte and Stanford [3]	Aeroelastic tailoring of transport aircraft wings: state-of-the-art and potential enabling technologies	A comprehensive review of sub-sonic transport aircraft wing's aeroelastic tailoring. The study focused on un-swept and swept-back wings, optimization algorithms, local and global tailoring, unconventional structural configurations, fibre tow-steered laminated composites, graded materials, and non-uniformly reinforced materials. Smart structures and materials, and active tailoring approaches have also been discussed briefly.	The study comprehensively summarized the works done in the preceding years, provided some further research guidelines, and discussed novel structural and material configurations, and smart structures and materials as enablers for the future of aeroelastic tailoring. The study provides a very good basis for research in aeroelastic tailoring, but the rapidly growing scientific knowledge and research warrant that such reviews be done every few years to consolidate the latest research and technological developments in this domain.
2017	Milhaila et al. [65]	Aeroelastic tailoring of composite aircraft wings	A short and crisp overview of seminal works in aeroelastic tailoring that provides a basis for future research work. The study focused on the aeroelastic tailoring concept, a basic mathematical model for composite materials with a description of coupling terms, optimization algorithms, and global and local tailoring concepts.	The study emphasized the importance of accounting for all constraints during tailoring optimization and predicted exponential growth of the applications with the advancements in computation and optimization. The damage tolerance and maintenance requirements were highlighted as potential focus areas for product life cycle management. The review is short and does not cite many works; however, it may serve as a starting point for new researchers in the domain of aeroelasticity.
2019	Li et al. [66]	An efficient implementation of aeroelastic tailoring based on efficient computational fluid dynamics-based reduced order model	A quick reduced order CFD-model-based aeroelastic tailoring instrument employed a structural dynamics re-analysis technique to update the analysis results for any structural design change. The prediction of aeroelastic behaviour and stability accurately for structural modifications against the baseline configuration of AGARD 445.6 wing under transonic flow conditions while economizing the computational costs.	It is important to update the aeroelastic model for the progressive changes in design during the tailoring optimization process. The feature is usually not supported by simple reduced-order models and a new model is required to be constructed for every design change. The proposed instrument may prove quite efficient for the evaluation of aeroelastic behaviour and tailoring requirements for major structural changes quickly and accurately. The current study used it for the AGARD 445.6 wing. The employment of the same for more complex configurations followed by complete aircraft models could further establish its practical utility. Once fully matured, this instrument could make the integration of the aeroelastic tailoring approach during the conceptual design phase a viable option, which has been desired by structural engineers for many decades.
2020	Melville et al. [67]	Aeroelastic Tailoring for Gust-Energy Extraction	The gust energy extraction from flexible sail-plane wing using aeroelastic tailoring. The explicit structural dynamics model combined with higher-order potential flow. Favourable changes in the neutral axis location and span-wise orientation. A 2–12% enhancement in energy extraction from the sinusoidal gust.	The study provided the basis for research on using aeroelastic tailoring for gains in gust-energy extraction. The gain in gust energy extraction was attributed to the forward shifting of the elastic axis that could affect divergence speed and aileron effectiveness. Moreover, the study used a simplified cantilevered beam model. The inclusion of static aeroelastic analysis (divergence speed and aileron effectiveness), and improvement in model configuration could provide a better assessment of the proposed methodology. Subsequently, the complete aircraft structure including engines and external stores also needs to be considered. The experimental testing and validation would then pave the way for its practical utilization.

(*continued on next page*)

Table 8 (*continued*)

Year	Author(s) [Ref]	Title	Emphasis	Comments
2022	Cheung et al. [68]	Improving horizontal stabilizer performance using aeroelastic tailoring	Designing and manufacturing horizontal stabilizer's aeroelastically tailored wind tunnel model. Optimization for improving lift-curve slope and enhancing the static aeroelasticity performance. Vibration testing for a non-optimized reference model and the manufactured model for updating the equivalent Finite Element (FE) models. The static aeroelastic behaviour prediction using the FE models. An 18% improvement in lift-curve slope and shifting of divergence conditions adequately beyond wind tunnel testing conditions.	The study provided a foundation for the application of aeroelastic tailoring for improving lift-curve slope and static aeroelasticity performance of fixed aircraft surfaces other than wing. The study considered stress constraints and the evaluation of flutter speeds for safety. The optimization could include buckling and strain constraints or analyses, followed by an analysis involving the complete aircraft structure. The concept may be used for aeroelastic tailoring of fixed surfaces other than wings to contribute towards the overall aircraft performance enhancement.
2022	Marano et al. [64]	Aeroelastic Tailoring of the Next Generation Civil Tiltrotor Technological Demonstrator Composite Wing	The next-generation civil tiltrotor's aeroelastic tailoring for whirl flutter, aeroelasticity, and strength requirements with a weight minimization objective (Fig. 7). Modal-strain-energy analyses. The use of ±45-degree orientation layers in locations with high strain energy in-plane torsion loading conditions and unidirectional layers in locations with out-of-plane flexural loading conditions. The proposed design fulfilled aeroelastic requirements with only about a 2.7% weight penalty.	The study adequately considered torsional and flexural stiffnesses, flutter, buckling, strength, and aeromechanical requirements. The proposed methodology could be extended to other tilt-rotor designs subject to validation through ground and flight testing.

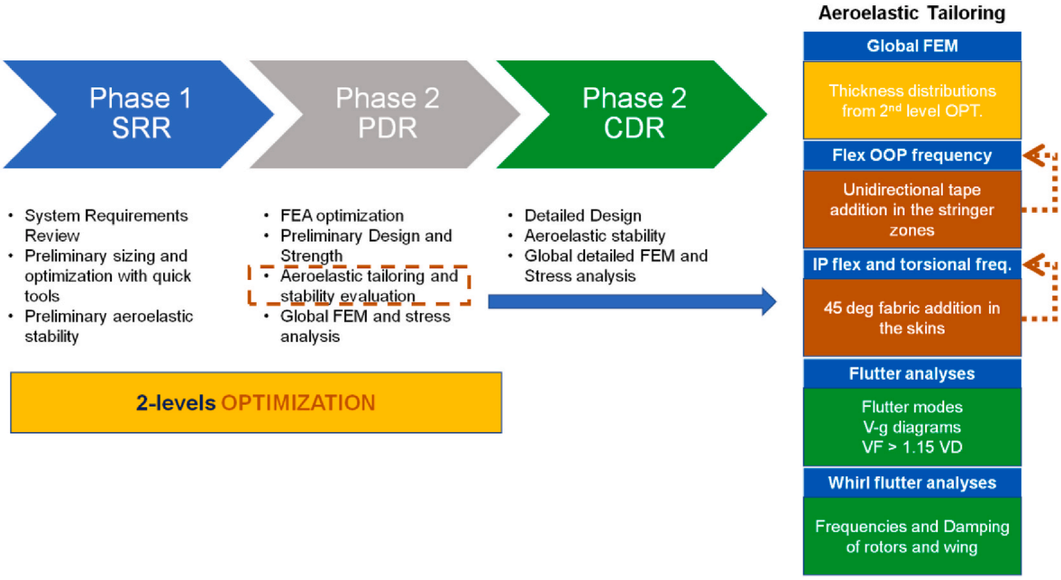

Fig. 7. Aeroelastic tailoring process of tilt-rotor (based on Ref [64]).

3.4. *Critical discussion, research needs, and futuristic outlook*

An overview of the works covered in Section 3 reveals that in recent years, the researchers have explored multiple dimensions, technologies, and applications of aeroelastic tailoring, multiplying the benefits and potential for future growth many times. The incorporation of novel tailoring optimization techniques (lamination parameters, blending constraints, active aeroelastic wing design, shape functions, surrogate modelling, reduced order modelling, uncertainty quantification, and numerous indigenous optimization algorithms), new material and structural technologies (curvilinear fibres, tow steering, additive manufacturing, unconventional structural configurations, selective reinforcing, thickness distributions, and functionally graded materials), diverse techniques (matrix perturbation theory, modal-strain-energy analyses, and CFD), and novel applications (horizontal stabilizer and tiltrotor design) have phenomenally expanded the scope of aeroelastic tailoring. Optimization of aeroelastic tailoring problems has evolved into a continuously flourishing research field. Novel materials and structural configurations are equally contributing to the cause of aeroelastic tailoring. The research in these domains has been growing over time and will continue to play a role in helping aeroelastic tailoring earn its rightful place in the design process.

A lot of research has been done in aeroelastic tailoring of various wing shapes like swept-forward, swept-back, joined-wing, cranked-arrow, lambda-wing, etc.; however, the trapezoidal wing design being used in the latest state-of-the-art aircraft is a less explored area. Moreover, the optimization of the aeroelastic tailoring problem is an area of concern. Optimization with lesser computational costs and better results, local vs. global optimization, skin or through-thickness optimization, material or structural optimization, higher-order robust optimization involving all design variables, configurations, and constraints, etc. remain the tasks for the researchers working in the domain of aeroelastic tailoring. The challenges faced for the full-scale employment of aeroelastic tailoring also include experimental validation of new methodologies, certification of new material and structural configurations through relevant bodies and standards, and gaining the confidence of industrialists for investment in technologies with a few highly focused areas of applications.

The futuristic outlook includes exploration of tailoring for novel wing designs and applications, continuation of research for improving the effectiveness and pace of the aeroelastic tailoring optimization process, and enhanced use of novel material and structural technologies. However, most of these techniques are still under test and trial. Caution must be exercised not to use the results of any work in isolation but to verify against other research in the field and to proceed with practical applications only after validation and the requisite certifications. The practical applications will also warrant a focus on damage tolerance and maintenance requirements for product life cycle management of the structures developed through new technologies. The maturity of these techniques and processes over time would lead to the integration of aeroelastic tailoring in the design process right from the onset and unprecedented expansion in aeroelastic tailoring applications.

4. Conclusion

Aeroelastic tailoring has come a long way from an unnamed concept about seven decades ago to a well-established field in the aerospace industry. The incorporation of new material and structural technologies like curvilinear fibres, tow steering, functional grading, thickness distributions, selective reinforcing, additive manufacturing, and unconventional structural configurations; and novel tailoring optimization techniques like lamination parameters, blending constraints, active aeroelastic wing design, shape functions, surrogate modelling, reduced order modelling, uncertainty quantification, matrix perturbation theory, modal-strain-energy analyses, and multiple indigenous optimization algorithms have exponentially broadened the scope of aeroelastic tailoring. The growth potential is enormous, and game-changers are around the corner. The researchers may use this review as a starting point for identifying the directions of their future endeavours, which are broadly the aeroelastic tailoring optimization process and the use of novel material and structural technologies. The challenges faced in the full-scale employment of aeroelastic tailoring include quick, robust, and cost-effective optimization to cater for all design variables and constraints, experimental validation of new methodologies, certification of new material and structural configurations through relevant bodies and standards, and gaining the confidence of industrialists for investment in technologies with a few highly focused areas of applications. The product life cycle management of the structures developed through new technologies could be another focus area. The maturity of these techniques and processes over time would lead to the integration of aeroelastic tailoring in the design process right from the onset and unprecedented expansion in aeroelastic tailoring applications.

Funding

Not applicable.

Data availability statement

This is a review article, and no data was used for the research described in the article.

Ethical approval

Not applicable.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Junaid Najmi: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Haris Ali Khan:** Writing – review & editing. **Syed Saad Javaid:** Writing – review & editing. **Asad Hameed:** Writing – review & editing. **Faisal Siddiqui:** Writing

– review & editing, Supervision.

Declaration of generative AI and AI-assisted technologies in the writing process

Not applicable.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Not applicable.

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