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Aeroelastic Tailoring of Transport Aircraft Wings: State-of-the-Art and Potential Enabling Technologies

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Aeroelastic Tailoring of Transport Aircraft Wings:
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This paper provides a brief overview of the state-of-the-art for aeroelastic tailoring of subsonic transport aircraft and offers additional resources on related research efforts. Emphasis is placed on aircraft having straight or aft swept wings. The literature covers computational synthesis tools developed for aeroelastic tailoring and numerous design studies focused on discovering new methods for passive aeroelastic control. Proprietary information, which is not available in the open literature, is understandably not included. Several new structural and material technologies are presented as potential enablers of aeroelastic tailoring, including selectively reinforced materials, functionally graded materials, fiber tow steered composite laminates, and various nonconventional structural designs. In addition, smart materials and structures whose properties or configurations change in response to external stimuli are presented as potential active approaches to aeroelastic tailoring.

1 Introduction

The Fixed Wing project of NASA's Fundamental Aeronautics program has been actively developing manufacturing techniques, new materials, and structural design tools to address a suite of technical challenges facing current and future subsonic transport aircraft. A primary challenge of the Fixed Wing project is to reduce fuel burn in transport aircraft. Targeted design advancements include wing structural weight reduction and increased wing aspect ratio to decrease lift-induced drag. High aspect ratio wings operating at minimum weight are typically highly flexible structures prone to aeroelastic instabilities. Therefore, aeroelastic tailoring is one important approach to achieve light weight airframe designs. Aeroelastic tailoring was defined as "*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,*" [1]. More simply, aeroelastic tailoring has also been defined as "passive aeroelastic control" [2]. In addition to stiffness, mass distribution also has an effect on the dynamic properties of a structure, although it is typically considered less during initial design efforts and more to mitigate harmful unforeseen dynamics found later in the design process. Weight minimization is only one objective associated with aeroelastic tailoring; other objectives include, but are not limited to, flutter, divergence, stress, roll reversal, control effectiveness, lift, drag, skin buckling, and fatigue.

The goal of this paper is to provide a brief overview on the state-of-the-art of aeroelastic tailoring for subsonic transport aircraft and to guide the reader to additional resources on related research efforts. Research areas are broken down as follows:

- Aeroelastic tailoring methods
    - Computational synthesis tools
    - Global (uniform) tailoring
    - Local (non-uniform) tailoring
    - Additional tailoring approaches
- Potential material/structural enabling technologies
    - Passive technologies, including selectively reinforced materials, functionally graded materials, fiber tow steering within composite laminates, and nonconventional structural designs
    - Active technologies

Material/structural enabling technologies for aeroelastic tailoring pertain to materials and structural designs that can directly affect a wing's stiffness, mass, or aerodynamics. The amount of research already dedicated to aircraft aeroelastic tailoring is substantial; furthermore, the extent of the research related to potential solutions or technologies for aeroelastic tailoring is even greater. Therefore, a limited timeframe of a few months was dedicated to perform a brief yet sufficient literature survey to guide NASA's current research in wing weight reduction. Proprietary information (which is not available in the open literate) is understandably not included. Of the research papers found, only the most relevant, which are usually the most recent, are included here.

Emphasis is placed on passive solutions to aeroelastic control of subsonic transport aircraft having straight or aft swept wings. Papers that approach aeroelastic tailoring in a more detailed and possibly localized manner (as opposed to globally reorienting the composite laminate of a wing skin, e.g.) are more heavily scrutinized and summarized here.

2 Aeroelastic Tailoring

According to Shirk et al. [1], the first record of aeroelastic tailoring is from 1949 by Munk [3] who oriented the grain of his wooden propeller blade to create desirable deformation couplings when operated. In the late 1960s, there was a thrust in aeroelastic tailoring research, which has continued fairly steadily through to today. The forward swept wings of the X-29 and the Active Aeroelastic Wing are two aeroelastic tailoring examples highlighted by Weisshaar [2]. Today the use of composite materials is becoming more prevalent in transport aircraft, including the 787, the A380, and the upcoming A350. Enhanced fabrication processes for composite laminates offer new design possibilities that have not been fully exploited for optimal aeroelastic performance and weight savings. Continued research into advanced aircraft materials and structures is likely to lead to new aeroelastically tailored designs. Table 1 lists papers on the broader subjects of aeroelastic tailoring, aeroelasticity, airframe materials, and/or airframe structural design. For additional information, the 'author' column also includes the number of references that were cited in a particular work.

Table 1. Papers on the broader subjects of aeroelastic tailoring, aeroelasticity, airframe materials, and/or airframe structural design.

Year	[Ref] Authors (#Cited works)	Title
1986	[1] Shirk, Hertz, Weisshaar (89)	Aeroelastic Tailoring – Theory, Practice, and Promise
2000	[4] Bucci, Warren, Starke (33)	Need for New Materials in Aging Aircraft Structures
2002	[5] Kuzmina, Amiryants, Schweiger, Cooper, Amprikidis, Sensberg (7)	Review and Outlook on Active and Passive Aeroelastic Design Concepts for Future Aircraft
2002	[6] Siochi, Anders, Cox, Jegley, Fox, Katzberg (116)	Biomimetics for NASA Langley Research Center: Year 2000 Report of Findings From a Six-Month Survey
2003	[7] Livne (508)	Future of Airplane Aeroelasticity
2003	[8] Livne, Weisshaar (205)	Aeroelasticity of Nonconventional Airplane Configurations
2004	[9] Renton, Olcott, Roeseler, Batzer, Baron, Velicki (14)	Future of Flight Vehicle Structures (2002-2023)
2009	[2] Weisshaar (35)	Aircraft Aeroelastic Design and Analysis – Chapter 1
2011	[10] Barbarino, Bilgen, Ajaj, Friswell, Inman (342)	A Review of Morphing Aircraft *(also included later in* Table 19*)*

2.1 Computational Synthesis Tools

Synthesis tools for aeroelastic tailoring have been developed to varying degrees of modeling fidelity. The literature emphasizes the following four tools as the most utilized: Wing Aeroelastic Synthesis Procedure (TSO), Wing Design Optimization with Aeroelastic Constraints (WIDOWAC), Flutter and Strength Optimization Procedure (FASTOP), and the Automated Structural Optimization System (ASTROS). ASTROS is still in development, and various versions have been utilized over its existence. Table 2 includes summaries of the three tools.

Table 2. Aeroelastic tailoring tools.

Tool [Ref]	Objective Function	Constraints	Structural Analysis
TSO [11]	"minimum weight skin thickness and composite ply orientations"*	"including strength, minimum gage, weight, lift-curve, flexible-to-rigid lift ratios, deflected shape, and flutter and divergence speeds"*	Ritz equivalent plate model*
WIDOWAC [12]	Minimum weight	Flutter, strength, minimum gage constraints	Finite element based
FASTOP [13]	Minimum weight*	Minimum gage, flutter, deflection*	Finite element based
ASTROS [14] - [16]	Modules for finite elements, smart structures, aerodynamics, sensitivity analysis, aeroservoelasticity, optimization, aeroelastic stability, trim analysis		Finite element based

* Ref. [1]

2.2 Global (Uniform) Tailoring

Figure 1 (from Ref. [17]) shows that certain aeroelastic tailoring methods can modify the wing's primary stiffness direction, changing the wing's bending and torsional stiffness as well as the degree of coupling between the two. The wing's primary stiffness direction is defined as the "locus of points where the structure exhibits the most resistance to bending deformation," [17]. The structural reference axis is the "conventional wing structure elastic axis," [17]. If the primary stiffness axis is not coincident with the structural reference axis, the wing will have bend-twist coupling. When the primary stiffness direction is moved forward of the structural reference axis, the bend-twist coupling causes the wing to have more "wash-out" (leading edge down) characteristics. When the primary stiffness direction is moved aft of the structural reference axis, the bend-twist coupling causes the wing to have more "wash-in" (leading edge up) characteristics [18]. Moving the primary stiffness axis in either direction produces desirable changes in wing performance, as labeled in Figure 1, but the two directions clearly involve trade-offs with one another.

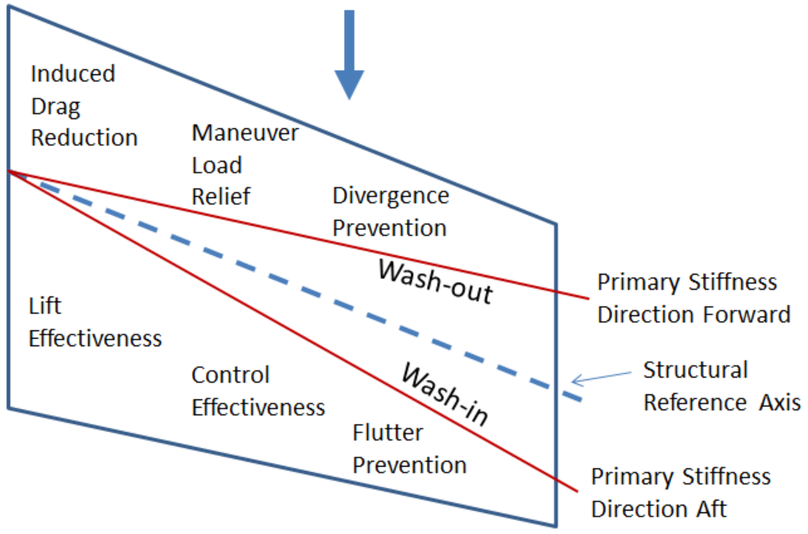


Figure 1. The effect that the location of the primary stiffness direction has on the characteristics of the wing (adapted from Ref. [17]).

Weisshaar, et al. [17] also discuss how the wing's sweep and it flexural axis relate to Figure 1, where the flexural axis is the "locus of points along the beam where, if a concentrated load were applied there, bending and twisting deformation combine to produce no additional angle of attack." The wing will tend to rotate about its flexural axis. With no built-in bend-twist coupling, the location of the flexural axis for a forward swept wing is aft of the location of aerodynamic loading, causing natural "wash-in" when the wing is loaded. For the aft swept wing, the location of the flexural axis is forward of the location of aerodynamic loading, causing natural "wash-out" when the wing is loaded. The location of the flexural axis will vary with the addition of bend-twist coupling. This is important in aeroelastic design since, "airloads applied close to this axis will be relatively uncoupled from the aerodynamic loads so that aeroelastic interaction is minimal," [17]. The fundamental work and more detailed explanations on this subject are found in Table 3.

Table 3. Papers covering the fundamental work and further details behind Figure 1.

Year	[Ref] Authors (#Cited works)	Title
1986	[19] Weisshaar, Ryan (9)	Control of Aeroelastic Instabilities Through Stiffness Cross-Coupling
1987	[20] Weisshaar (49)	Aeroelastic Tailoring - Creative Uses of Unusual Materials
1998	[17] Weisshaar, Nam, Batista-Rodriguez (38)	Aeroelastic Tailoring for Improved UAV Performance

Table 4 includes examples of optimization routines or parametric studies that vary the global (as opposed to the local panel level) composite ply orientations or ply sequence on straight or aft swept wings, which is somewhat similar to the approach taken on the forward swept wings of the X-29. The last column summarizes the general approach of a particular effort. The results were usually positive, although Eastep et al. [21] found that the optimal composite structural configurations are fairly insensitive to laminate orientations when imposing various constraints. Some papers focused on the challenges of optimizing in a discontinuous design space since small alterations in wing design can change the active constraint from flutter to either divergence or another flutter mode. Ghiasi et al. [22] provides a review on various approaches used for optimizing the constant stiffness of composite laminates.

Weisshaar et al. [17] performed parametric studies on a wing (modeled as a beam) in order to reduce induced drag and increase the control reversal speed by considering a stiffness cross coupling parameter, wing sweep, wing taper, aspect ratio, airspeed, and leading/trailing edge control. Strength, in terms of elastic stress-based failure, was not considered. The main findings were as follows:

- "The amount of stiffness coupling required [to reduce induced drag] is relatively small."
- "Aeroelastic tailoring can increase the control reversal speed of swept wings and that different laminate designs are needed depending on whether leading edge or trailing edge controls are used."
- Considering an Unmanned Air Vehicle (UAV), "Aeroelastic tailoring may not produce a structure with a drastically reduced weight compared to an untailored structure. However, the vehicle performance that is possible with tailoring may produce the innovative, low-cost design with nearly the same weight but with improved performance. However, to be effective, aeroelastic interaction must be large; we may be required to operate close to the divergence speed at a given altitude or have noticeable wing flexibility."
- "When the aspect ratio is large, tailoring is less effective [with regard to induced drag] and the effects of wing distortion on induced drag are more difficult to control."
- "Although an elliptically shaped lift distribution creates the least induced drag, when compromising for minimum weight (as in aircraft design) the optimal lift distribution becomes more triangular."

Table 4. Global aeroelastic tailoring papers that vary the ply orientations of composite wing skins.

Year	[Ref] Authors (#Cited works)	Title	General approach/emphasis
1987	[23] Green (14)	Aeroelastic Tailoring of Aft-Swept High-Aspect-Ratio Composite Wings	Parametric study
1989	[24] Isogai (16)	Direct Search Method to Aeroelastic Tailoring of a Composite Wing under Multiple Constraints	Optimization – Discontinuous design space (flutter and divergence modes)

1999	[25] Visser (16)	Aeroelastic and Strength Optimisation of a Composite Aircraft Wing Using a Multilevel Approach	Optimization – positive outcome
1999	[21] Eastep, Tischler, Venkayya, Khot (10)	Aeroelastic Tailoring of Composite Structures	Optimization – negative outcome
2002	[26] Qin, Marzocca, Librescu (28)	Aeroelastic Instability and Response of Advanced Aircraft Wings at Subsonic Flight Speeds	Parametric study – a focus on warping restraint
2004	[27] Hirano, Todoroki (23)	Stacking Sequence Optimizations for Composite Laminates Using Fractal Branch and Bound Method: Application for Supersonic Panel Flutter Problem with Buckling Load Condition	Optimization – positive outcome
2005	[28] Kim, Hwang (17)	Optimal Design of Composite Wing Subjected to Gust Loads	Optimization – positive outcome
2006	[29] Seresta, Abdalla, Mulani, Marzocca (33)	Stacking Sequence Design of Flat Composite Panel for Flutter and Thermal Buckling	Optimization – positive outcome
2007	[30] Kim, Oh, Kweon, Choi (5)	Weight Optimization of Composite Flat and Curved Wings Satisfying Both Flutter and Divergence Constraints	Optimization – positive outcome
2007	[31] Kameyama, Fukunaga (19)	Optimum Design of Composite Plate Wings For Aeroelastic Characteristics Using Lamination Parameters	Optimization – discontinuous design space (flutter and divergence modes)
2008	[32] Manan, Cooper (44)	Uncertainty of Composite Wing Aeroelastic Behaviour	Optimization – positive outcome
2009	[33] Harmin, Cooper (19)	Aeroelastic Tailoring Using Ant Colony Optimization	Optimization – positive outcome
2009	[22] Ghiasi, Pasini, Lessard (139)	Optimum Stacking Sequence Design of Composite Materials, Part 1: Constant Stiffness Design	A review of optimization routines used for determining constant stiffness designs of composite laminates
2011	[34] Attaran, Majid, Basri, Mohd Rafie, Abdullah (18)	Structural Optimization of an Aeroelastically Tailored Composite Flat Plate Made of Woven Fiberglass/Epoxy	Parametric study

2.3 Local (Non-uniform Tailoring)

When separate sections of the wing are tailored differently from one another, aeroelastic tailoring is applied in a more “local” manner over the wing. The following four tables list references that pertain to this less common, local approach to aeroelastic tailoring. Certain local approaches to wing structural design are not included here but in a later section, since they did not explicitly account for aerodynamic interactions. Table 5 covers papers that vary ply orientations of separate composite laminate panels (as opposed to one “global” panel) making up the wing’s skin. Table 6 provides papers that utilize non-conventional structural topologies. By comparing the topologies among these designs, general insights into the best arrangement of structure and stiffness may be possible. Table 7 considers the employment of various aeroelastic tailoring techniques into a single study or optimization routine. In particular, De Leon et al. [35] studies extremely localized aeroelastic tailoring by orienting composite fibers at the elemental level. Finally, Table 8 covers papers that utilize highly idealized wing models, such as simple 1D beams where the optimal thickness of each beam section is determined.

Table 5. Aeroelastic tailoring papers using varying ply orientations amongst separate composite panels.

Year	[Ref] Authors (#Cited works)	Title	Summary
2006	[36] Guo, Cheng, Cui (17)	Aeroelastic Tailoring of Composite Wing Structures by Laminate Layup Optimization	• Conducted a parametric study on a wing box comprised of 20 different panels. Varied the wing planform and also optimized the laminate fiber orientations over each panel. • The weight of each wing box was constant. • Utilized gradient and discrete optimization methods to optimize for maximum flutter speed. • The results are summarized in Figure 3 (of the paper). The quasi-isotropic laminate [0/-45/45/90]° had the worst results. Maximum torsional rigidity [-45/45]° showed much improvement. Best results came from optimizing each panel individually. Optimized designs are summarized by their calculated EI (bending stiffness), GJ (torsional stiffness), and CK (coupling rigidity). When performing aeroelastic tailoring, it is more effective to optimize CK for straight wings and GJ for swept wings. • Did not consider structural strength or skin buckling.
2007	[37] Guo (26)	Aeroelastic optimization of an aerobatic aircraft wing structure	• Performed optimization on a wing comprised of 24 panels (6 spanwise by 4 circumferentially). Each panel had 8 plies. • Results show that wings with the highest flutter speed have increased torsional rigidity (GJ) and decreased bending rigidity (EI). This would separate the uncoupled bending and torsional frequencies, increasing the flutter speed at which they coalesce. Wings with highest flutter speed also had some bend-twist coupling (CK). • The results indicate that the optimization routines did not reach global optimums (for example, the design space of case 1 included the design space of case 2, yet the final result of case 2 was better than case 1), thus nothing can be concluded here about the benefits or shortcomings of varying fiber angles per spanwise wing section.
2007	[38] Herencia, Weaver, Friswell (51)	Morphing Wing Design via Aeroelastic Tailoring	• Optimized a composite wing box having 5 segments from root to tip. Each skin and spar panel was optimized for ply sequence (flexural anisotropy) and ply volume fraction (membrane anisotropy) using only 0°, +45°, -45° and 90° ply orientation permutations. • Optimized first for only structural constraints (strength, buckling, practical design, etc.). Optimized second for both structural and aerodynamic (lift and drag) constraints. • In areas of higher buckling, there was less use of anisotropy. When more anisotropy was used, the wing panels were typically thicker. Consequently, drag was able to be reduced by 1.4% but weight was increased by 18.7%.

2010	[39] Chang, Yang, Wang, Wang (32)	Design Optimization of Composite Wing Box for Flutter and Stiffness	• Optimized three composite wing boxes each having 5 segments from root to tip. One wing box was constrained to have uniform thickness across the 5 segments. Three studies were performed on each wing box to determine optimum fiber orientations. • The weight of each wing box was constant. • Utilized a genetic algorithm to optimize for maximum flutter speed and minimum tip deflection simultaneously. • Designs with the maximum flutter also had the most tip deflection. • Comparisons cannot be made between the 1st study and the other two studies since the thickness per ply was not constant. Comparing the results of the 2nd and 3rd study suggest that optimizing the fiber orientation per panel, verses keeping it uniform across the panels, increases flutter speed. • The wing box of uniform thickness had highest flutter speeds, and its panels closer to the root had greater impact on flutter. For the nonuniform thickness wing boxes, the panels furthest from the root had greater impact on flutter. • Did not consider strength or skin buckling. Plans for more studies using additional load cases and objectives.

Table 6. Aeroelastic tailoring papers using isotropic materials and structural design optimization.

Year	[Ref] Authors (#Cited works)	Title	Summary
1975	[40] Haftka (10)	Parametric Constraints with Application to Optimization for Flutter Using a Continuous Flutter Constraint	• Used WIDOWAC to compute the optimal thickness distribution of a low aspect ratio titanium wing with a beryllium patch. • Wing mass was minimized subject to a flutter constraint • Results indicate that, due to the discontinuous nature of the aeroelastic flutter mechanism (i.e., the advent of hump modes, or the loss of criticality of a conventional flutter mechanism), an equivalent nonparametric "minimum value" constraint is preferred to a conventional flutter-based parametric constraint.
2002	[41] Stroud, Krishnamurthy, Mason, Smith, Naser (11)	Probabilistic Design of a Plate-Like Wing to Meet Flutter and Strength Requirements	• Developed a reliability-based design approach to aeroelastic tailoring of a metallic plate-like wing. • Minimized weight by varying the wing thickness distribution using nine locations on the wing. • Determined that reliability can be increased with relatively small increases in weight. • Figures 7 and 12 (in the paper) show two designs with similar weight but different load paths. The thickest regions are the leading edge at midspan and the root. The thinnest regions are the rear trailing edge, the tip, and the very forward root area. • Considered strength and flutter.
2004	[42] Martins, Alonso, Reuther (23)	High-Fidelity Aerostructural Design Optimization of a Supersonic Business Jet	• Reduced weight on a natural-laminar flow supersonic business jet by employing multidisciplinary design optimization. • Minimized weight and drag simultaneously by optimizing the OML and spar/rib thicknesses and depths. • The surface density distribution of the optimized wing in Figure 12 (of the paper) shows more material toward the leading edge at both the midspan and tip. • Considered strength and aeroelasticity. Utilized previously developed analysis tools. Did not consider flutter and skin buckling.

2004	[43] Maute, Allen (61)	Conceptual Design of Aeroelastic Structures by Topology Optimization	• Performed two examples of topology optimization. • The first example showed that fluid-structure interaction cannot be overlooked when performing aeroelastic tailoring. When including this interaction, drag was reduced and the topology showed one thick spar that terminated at the leading edge where additional material was also located. • The second example minimized mass by identifying areas in the spars and ribs that can be less stiff. The results showed that ribs were stiffer toward the outboard of the wing and the spars were stiffer toward the inboard of the wing. The ribs had the greatest stiffness at the leading edge and underside of the wing, where the pressures are greater. • Considered stress and aerodynamics. Did not account for flutter nor buckling of skin and stiffeners.
2005	[44] Okada, Furuya (21)	Robust Structural Optimization of Plate Wing Corresponding to Bifurcation in Higher Mode Flutter	• Developed robust structural design optimization of a constant mass, varying thickness plate-like delta wing to maximize the critical dynamic speed associated with supersonic flutter. • Increased the flutter speed by 6 times. • Improved convergence by constraining adjacent modes to be a constant distance apart from one another. • Future work will consider the effects of damping. Did not consider strength.
2008	[45] Gomes, Suleman (27)	Topology Optimization of a Reinforced Wing Box for Enhanced Roll Maneuvers	• Developed a level-set method to reinforce the upper skin of a wing torsion box for increased aileron reversal dynamic pressure. • Optimized the thickness variation over the upper surface. • Utilized COBYLA, a derivative-free optimization tool. • Despite different initial designs, the optimizer always led to material reinforcement at the leading and trailing edges. • Considered only torsional loads to simulate aerodynamic loads. Did not consider stress, skin buckling, and flutter constraints.
2009	[46] Kobayashi, Pedro, Kolonay, Reich (27)	On a Cellular Division Method for Aircraft Structural Design	• Developed a biologically inspired topology optimization method that breaks a wing structure into “cells”. • Utilized a wing box model of a generic fighter aircraft and varied the topology variables, thicknesses, and stiffnesses via a genetic algorithm. • Displayed results by using a Pareto set between mass and stress. With additional mass available, more stiffeners were added in the optimization verses adding more structural thickness. • Utilized the doublet lattice method. Did not indicate flutter as a constraint. Did not consider skin buckling.
2011	[47] Stanford, Beran (23)	Optimal Structural Topology of a Plate-Like Wing for Subsonic Aeroelastic Stability	• Studied the Pareto front between mass and aeroelastic instability using an aluminum plate of different planforms. • Varied the thickness of each element. • Experienced slower convergence due to switching between resultant flutter and divergence modes while using a gradient based optimizer. • The optimized variable thickness wing was always better than the uniform-thickness wing. • The straight and aft-swept wings had some similarities, including the following: most of the mass was towards the leading edge, lower mass designs have rib-like distributions of mass, and the mass at the root is focused at the leading and trailing edges. • Considered flutter but did not include strength as a constraint.

2011	[48] Harmin, Ahmed, Cooper, Bron (13)	Aeroelastic Tailoring of Metallic Wing Structures	• Varied the unidirectional orientation of the ribs and skin crenulations (ridges) in both rectangular and tapered wing boxes to assess their effects on flutter speed and bending and twist deflection. • The structural weight was constrained as a constant. • Demonstrated bending and torsion coupling and also increased flutter speed by 3%. • Did not consider stress, skin buckling, or the variation of orientations between adjacent ribs or crenulations.
2012	[49] Stanford, Beran (39)	Computational Strategies for Reliability-Based Structural Optimization of Aeroelastic Limit Cycle Oscillations	• Optimized the thickness distribution of a cantilevered plate in supersonic flow for minimum mass. • Used a constraint on the nonlinear post-flutter limit cycle oscillation amplitude, rather than the flutter point itself. • Considered both deterministic LCO constraints, as well as probabilistic (i.e., the probability that an LCO amplitude will be larger than required). • Utilized proper orthogonal decomposition (POD)-based model reduction and time-periodic spectral elements to reduce LCO optimization cost. • Low-mass plates with feasible LCO amplitudes were found by lumping mass along the leading edge of the wing. A very minor increase in the leading edge material could drop the probability of LCO failure substantially.
2012	[50] Sleesongsom, Bureerat (33)	New Conceptual Design of Aeroelastic Wing Structures by Multi-Objective Optimization	• Used structural sizing and topology variables to solve multi-objective aeroelastic optimization problems for wing weight, buckling, and lift effectiveness. • Considered constraints on divergence, flutter, and stress metrics. • Topological variables based on a ground structure approach, and was found to give superior designs to those with just conventional sizing variables, via a multi-objective population-based incremental learning algorithm.
2013	[51] Dunning, Brampton, Kim (20)	Multidisciplinary Level Set Topology Optimization of the Internal Structure of an Aircraft Wing	• Used level set methods to find the optimal internal distribution of material within a rectangular aeroelastic wing box. • Element mesh composed of tri-linear finite elements, which could appear or disappear during the optimization: design problem was to minimize compliance subject to a weight and a lift constraint. • Optimal topology was not found to have rib and spar-like patterns (instead large sections of mass were lumped along the root and/or tip), though results are preliminary.

Table 7. Aeroelastic tailoring papers using tailoring techniques that are not specific to a single category.

Year	[Ref] Authors (#Cited works)	Title	Summary
1991	[52] Bohlmann, Scott (8)	A Taguchi Study of the Aeroelastic Tailoring Design Process	• Implemented a Taguchi Method to determine important design components to consider when aeroelastically tailoring a generic F-16 wing model. • Considered laminate orientation, ply thickness, built in camber, control surface deflections, and others. • Evaluations included weight, roll rate effectiveness, hinge moment effectiveness, roll damping flex-to-rigid ratio, and others. Utilized TSO (tool) for determining strength, flutter, and roll moment effectiveness. • One conclusion states that when the laminate orientations are not constrained, the structural weight increases. For example, the bi-directional laminate [-45/45]° which had the best torsional rigidity required additional plies to compensate for its low bending rigidity. • Provides design guidelines but the study is “not all encompassing.”
1992	[53] Rehfield, Chang, Zischka (12)	Modeling And Analysis Methodology For Aeroelastically Tailored Chordwise Deformable Wings	• Introduced enhanced-lift design concepts that elastically increase camber when bent or twisted. “Elastically produced camber is created by establishing a differential chordwise membrane strain between the upper and lower box covers while preserving the structural box.” • In the bending example of a generic transport wing, the ‘Exaggerated Poisson’s Effect’ is produced by both composites and the orientation of unidirectional stiffeners. • Performed an experiment on a wing box to validate the analysis methodology for the bending-camber concept. • Considers stress, skin buckling, and divergence. Did not account for flutter. • Appendix D (in the paper) provides rib concepts for the proposed designs.
2005	[54] Arizono, Isogai (14)	Application of Genetic Algorithm for Aeroelastic Tailoring of a Cranked-Arrow Wing	• Developed a genetic algorithm to optimize the laminate orientation and the spar, rib, and skin thicknesses of a cranked-arrow wing of a supersonic jet for minimum structural weight. • To minimize the number of design variables, the wing was subdivided into regions of uniform structural thicknesses. • The inclusion of laminate orientations provided additional weight reduction. • Considered strength, local buckling, and flutter constraints.
2012	[55] Kennedy, Martins (32)	A Comparison of Metallic and Composite Aircraft Wings using Aerostructural Design Optimization	• Multidisciplinary design optimization of a high aspect ratio subsonic transport wing box, using either metallic structures or composite structures. • Obtained the Pareto front between fuel burn and gross take-off weight via wing shape and wing structure variables, under trim constraints, strength constraints, and skin buckling constraints, but did not consider flutter. • Extra design freedom afforded by orthotropic composites was found to provide sizeable improvements in aspect ratio, weight, and fuel burn.

2012	[35] De Leon, de Souza, Fonseca, da Silva (42)	Aeroelastic Tailoring Using Fiber Orientation and Topology Optimization	• Optimized laminated flat plate designs by first optimizing elemental fiber orientations for increased flutter speed and then by optimizing the elemental material density for minimum weight. • Developed a procedure to exploit tow steering fabrication. • Increased the flutter speed by maximizing the eigenvalue associated with the eigenmode involved with the flutter onset. • Tools included ZAERO (including ZONA 6 unsteady lifting surface method). • Did not consider strength.
2013	[56] Dillinger, Klimmek, Abdalla, Gürdal (32)	Stiffness Optimization of Composite Wings with Aeroelastic Constraints	• Optimized stacking sequence of wing skins for either mass or aileron effectiveness, with constraints on laminate failure and buckling. • Gradient based optimization via response surface methods, with the elements of the in-plane and the bending stiffness matrices used directly as design variables. • Unbalanced laminates showed superior performance over balanced for all optimization problems.

Table 8. Aeroelastic tailoring papers having simplified, highly idealized wing models, typically comprised of 1D beam elements.

Year	[Ref] Authors (#Cited works)	Title
1982	[57] Seyranian (42)	Sensitivity Analysis and Optimization of Aeroelastic Stability
1988	[58] Craig, McLean (8)	Spanload Optimization for Strength Designed Lifting Surfaces
1996	[59] Butler, Banerjee (13)	Optimum Design of Bending-Torsion Coupled Beams with Frequency or Aeroelastic Constraints
1999	[60] Barboni, Mannini, Gaudenzi (11)	On the Use of the P-TFE Method for Panel Flutter Optimization
1999	[61] Langthjem, Sugiyama (21)	Optimum Shape Design Against Flutter of a Cantilevered Column With an End-Mass of Finite Size Subjected to a Non-Conservative Load
2004	[62] Lemanski, Weaver (5)	Flap-Torsion Coupling in Prismatic Sections
2006	[63] Palaniappan, Beran, Jameson (9)	Optimal Control of LCOs in Aero-Structural Systems
2007	[64] Pastilha (45)	Structural Optimization for Flutter Instability Problems
2013	[65] Stanford, Beran (37)	Direct Flutter and Limit Cycle Computations of Highly-Flexible Wings for Efficient Analysis and Optimization

2.4 Additional Tailoring Approaches

This section covers a variety of research papers that are relevant to aeroelastic tailoring but are not directly applicable to either global or local tailoring or the goal of weight reduction in transport aircraft. Table 9 includes research papers on the accurate weight calculation of aircraft. Table 10 provides research papers on the aeroelastic tailoring of micro air vehicles. Table 11 includes additional papers concerning aeroelastic tailoring that have insightful conclusions that are important to consider during wing design. Finally, Table 12 covers papers that are relevant to modeling, analysis, and optimization of aeroelastically tailored structures.

Table 9. Research on accurate weight calculation of aircraft.

Year	[Ref] Authors (#Cited works)	Title
2000	[66] Boynton, Weiner (3)	Measuring Mass Properties of Aircraft Control Surfaces
2004	[67] Regis, de Mattos (28)	Wing Structural Weight Evolution With The Cruise Mach Number Of A Commercial Transport Aircraft

Table 10. Aeroelastic tailoring of micro air vehicles.

Year	[Ref] Authors (#Cited works)	Title
2008	[68] Stanford, Ifju (148)	Fixed Membrane Wings for Micro Air Vehicles: Experimental Characterization, Numerical Modeling, and Tailoring
2009	[69] Stanford, Ifju (34)	Aeroelastic Topology Optimization of Membrane Structures for Micro Air Vehicles
2009	[70] Stanford, Ifju (27)	Multi-Objective Topology Optimization of Wing Skeletons for Aeroelastic Membrane Structures

Table 11. Relevant outcomes of aeroelastic tailoring work.

Year	[Ref] Authors (#Cited works)	Title	Summary
2001	[71] Inglesias, Mason (18)	Optimum Spanloads Incorporating Wing Structural Weight	Concluded that when minimizing weight, optimizing the spanloads to reduce root bending moment is more effective than optimizing spanloads for reduced drag.
2003	[72] Pettit, Grandhi (20)	Optimization of a Wing Structure for Gust Response and Aileron Effectiveness	Optimized for weight reduction with gust response and aileron effectiveness constraints. Future work will include stress and flutter considerations. "[A result] indicates that the structure's aeroelastic properties are much more sensitive to Young's modulus variability in the skin panels than to variability in their thickness or spar and rib thickness."
2004	[73] Papila, Haftka, Mason, Alves (12)	Tailoring Wing Structures for Reduced Drag Penalty in Off-Design Flight Conditions	Optimized a wing for reduced drag and had better results when considering off-design flight conditions instead of a single flight condition.
2005	[74] Love, Zink, Wieselmann, Youngren (8)	Body Freedom Flutter of High Aspect Ratio FlyingWings	Did not have success with aeroelastically tailoring a flying wing aircraft to delay body freedom flutter, although it is mentioned that too many simplifications may have been made, including not accounting for weight addition when adding stiffness. Promotes active aeroelastic tailoring.
2012	[75] Wang, Liu, Tang, Yang (15)	The Influence of Spar Position on Aeroelastic Optimization of a Large Aircraft Wing	Found that the position of the leading edge spar had a far greater impact on the aeroelastic optimization process than the trailing edge spar. Results indicated better designs with composite wings, as compared to metallic, but the optimal wing weight of both increased substantially if design constraints were difficult to satisfy.

Table 12. Modeling, analysis, and optimization approaches for aeroelastic tailoring.

Year	[Ref] Authors (#Cited works)	Title	Emphasis
1989	[76] Livne (6)	An Integrated Approach To The Optimum Design Of Actively Controlled Composite Wings	Multidisciplinary design, analysis, and optimization (MDAO)
1998	[77] Komarov, Weisshaar (18)	Aircraft Structural Design - Improving Conceptual Design Level Fidelity	MDAO
1998	[78] Blair, Hill, Weisshaar (10)	Rapid Modeling with Innovative Structural Concepts	Model – (includes organic wing design)

1999	[79] Livne, Navarro (24)	Nonlinear Equivalent Plate Modeling of Wing Box Structures	Model
1999	[80] Reuther, Alonso, Martins, Smith (28)	A Coupled Aero-Structural Optimisation Method for Complete Aircraft Configurations	MDAO
2001	[81] Gumbert, Hou, Newman (42)	Simultaneous Aerodynamic and Structural Design Optimization (SASDO) for a 3-D Wing	MDAO
2009	[82] Demasi, Livne (65)	Dynamic Aeroelasticity of Structurally Nonlinear Configurations Using Linear Modally Reduced Aerodynamic Generalized Forces	Analysis
2010	[83] Yoon (46)	Topology Optimization for Stationary Fluid-Structure Interaction Problems using a New Monolithic Formulation	MDAO
2010	[84] Fazelzadeh, Marzocca, Mazidi, Rashidi (19)	Divergence and Flutter of Shear Deformable Aircraft Swept Wings Subjected to Roll Angular Velocity	Analytical model
2011	[85] Seeger, Wolf (27)	Multi-Objective Design of Complex Aircraft Structures Using Evolutionary Algorithms	MDAO
2012	[86] Bhatia, Kapania, Haftka (17)	Structural and Aeroelastic Characteristics of Truss-Braced Wings: A Parametric Study	MDAO
2012	[87] Daoud, Petersson, Deinert, Bronny (12)	Multidisciplinary Airframe Design Process: Incorporation of Steady and Unsteady Aeroelastic Loads	MDAO

3 Potential Enabling Technologies of Aeroelastic Tailoring

This section highlights technologies that can directly affect a wing's stiffness, mass, or aerodynamics, although not all papers below explicitly account for aerodynamic loading. If a technology does not require controls for aeroelastic tailoring purposes, it is considered 'passive'. Otherwise, the technology is considered 'active'. The following sections are broken down by this active/passive distinction.

3.1 Passive

Various developments in materials and structures may contribute to the aeroelastic tailoring of wings for further weight reduction and improved performance. This section introduces various potential enabling technologies, including: selectively reinforced materials, functionally graded materials, fiber tow steered composite laminates, and various nonconventional structural designs.

3.1.1 Selectively Reinforced Materials

Selectively reinforced materials are a particular type of composite material. One example is metal matrix composites (MMCs), which are metals or alloys that are reinforced by another material. Porous metals, also called metal foams or microcellular metals, are also included within this category [88]. MMCs have been applied to various aeronautic vehicles, including the ventral fin of the F-16 [89]. These composites take advantage of the best properties of their individual constituents, but their usage is limited due to their relatively high manufacturing cost [90]. Table 13 and Table 14 list brief summaries of papers relevant to either MMCs in general or their application in aerospace. There is no record of MMCs being used specifically for the aeroelastic tailoring of wings.

A subset of MMCs is fiber metal laminates (FMLs). A common example is GLARE, a "Glass Laminate Aluminium Reinforced Epoxy", which is comprised of layers of glass fiber that are interspersed and bonded between layers of metal [91]. Like MMCs, the composite laminates have attractive properties, but are relatively expensive. However, GLARE is currently used in the upper fuselage skin of the A380 [92]. Table 15 and Table 16 list brief summaries of papers relevant to either GLARE or its integration into aerospace applications.

Finally, Reinforced Core Sandwich (RCS) and Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) panels are two specific examples of lightweight, reinforced constructions of materials. Bednarcyk et al. [93] developed and verified a tool to incorporate and size RCS and PRSEUS panels for lightweight designs. They describe the two reinforcement methods as follows:

- “Reinforced core sandwich (RCS) panels combine aspects of foam core sandwich panels and stiffened panels in a concept that includes integral composite webs for optimum through thickness shear capabilities and excellent damage tolerance.”
- “Boeing’s Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) panels rely on pre-cured unidirectional composite rods for high axial stiffness, integral foam core frames of transverse support, and stitching for superior damage tolerance.”

Table 13. Papers on the state-of-the-art and aeronautical applications of MMCs.

Year	[Ref] Authors (#Cited works)	Title	Overview
1991	[94] Ibrahim, Mohamed, Lavernia (127)	Particulate Reinforced Metal Matrix Composites - a Review	Describes the state-of-the-art of particulate reinforced MMCs as of 1991. Provides historic examples of weight savings. Presents physical and material properties.
1997	[95] Degischer (20)	Innovative Light Metals: Metal Matrix Composites and Foamed Aluminum	Describes particulate reinforced light metals, continuous fiber reinforced light materials, and aluminum foam.
2001	[89] Miracle (1)	Aeronautical Applications for Metal Matrix Composites	Describes aeronautical applications of MMCs, including the use in the ventral fin on the F-16. The MMC design had a 40% increase in specific stiffness and reduced the tip deflection by 50%.
2005	[90] Miracle (47)	Metal Matrix Composites – From Science to Technological Significance	Describes the state-of-the-art of MMCs as of 2005. States that many of the technical challenges of MMCs have been overcome or minimized, although their cost is still relatively high. Figure 1 (in the paper) compares the stiffness vs. strength properties of metals and MMCs. Provides examples of applications of MMCs, including selective reinforcement of an engine block. Explains that MMC’s can be functionally graded.
2010	[88] Mortensen, Llorca (140)	Metal Matrix Composites (Annual Review)	Describes the state-of-the-art as of 2010. Provides a thorough introduction of MMCs and their benefits. Describes newly developed MMC materials and the research focused on understanding the physics and micromechanics of these materials. Microcellular metals (metal foams) have seen a recent thrust in research.

Table 14. Recent but less relevant papers on MMCs.

Year	[Ref] Authors (#Cited works)	Title	Emphasis
2000	[96] Kaczmar, Pietrzak, Wlosinski (68)	The Production and Application of Metal Matrix Composite Materials	Overview on MMCs
2001	[97] Rawal (10)	Metal-Matrix Composites for Space Applications	Space applications of MMCs
2009	[98] Fernández, González-Doncel (38)	Additivity of Reinforcing Mechanisms During Creep of Metal Matrix Composites: Role of the Microstructure and the Processing Route	Creep in MMCs
2009	[99] Scherm, Völkl, van Smaalen, Mondal, Plamondon, L’Espérance, Bechmann, Glatzel (20)	Microstructural Characterization of Interpenetrating Light Weight Metal Matrix Composites	MMCs at the microstructural level
2012	[100] Ricks, Lacy, Bednarcyk, Arnold (14)	A Multiscale Modeling Methodology for Metal Matrix Composites Including Fiber Strength Stochastics	Modeling MMCs

Table 15. Papers on the state-of-the-art and aeronautical applications of GLARE.

Year	[Ref] Authors (#Cited works)	Title	Overview
2007	[101] Slingerland, Alkemadey, Vermeulenz (11)	A Preliminary Prediction Method for the Effect of New Fuselage Materials on Transport Aircraft Weight	Developed a method for predicting aircraft weight when fuselage materials are either metals or fiber metal laminates like GLARE. Describes the composition and material properties of GLARE. Conclusion provides estimated aircraft weight savings when using GLARE.
2008	[92] Alderliesten, Benedictus (46)	Fiber/Metal Composite Technology for Future Primary Aircraft Structures	Describes the state-of-the-art as of 2008. States that GLARE is tailorable. Emphasizes that damage tolerance must be considered when making aircraft weight assessments between materials. Provides a good description of the benefits of combining the two materials: "Metals have a high bearing strength and impact resistance and are easy to repair, whereas full composites have excellent fatigue characteristics and high strength and stiffness."

Table 16. Additional papers on GLARE.

Year	[Ref] Authors (#Cited works)	Title	Emphasis
2003	[102] Schmidt, Schmidt-Brandecker (4)	Damage Tolerant Design And Analysis Of Current And Future Aircraft Structure	Damage requirements, GLARE vs. aluminum comparison
2010	[103] Seo, Hundley, Hahn, Yang (17)	Numerical Simulation of Glass-Fiber-Reinforced Aluminum Laminates with Diverse Impact Damage	Damage considerations, modeling GLARE

3.1.2 Functionally Graded Materials

Functionally graded metals are especially beneficial to high temperature applications like supersonics since they eliminate discrete changes in the coefficient of thermal expansion which can cause significant stress at the boundary between two adjacent materials [104]. Marzocca, et al. provides a literature survey on nonlinear aero-thermal-elasticity of functionally graded panels. The survey's relevance is limited though since the extent of functional grading is modeled by a simple volume fraction parameter. Also, the benefits did not cover subsonic transports or detailed wing designs [104].

A paper by Venkataraman and Sankar [105] demonstrates the benefits of reinforcing a hole with continuously graded material. New manufacturing processes, such as the electron beam freeform fabrication (EBF^3) [106], are helping to enable the fabrication of functionally graded metals. Pettit and Grandhi [72] concluded that a wing "structure's aeroelastic properties are much more sensitive to Young's modulus variability in the skin panels than to variability in their thickness or spar and rib thickness." For this reason, the grading of the Young's modulus may be very effective in aeroelastic tailoring efforts, at least for the configuration considered in [72].

3.1.3 Fiber Tow Steering

Fiber tow steering is a fabrication process that enables fibers of a composite laminate to be applied along curvilinear paths within a single ply. This adds increased design freedom in composite laminate design. The earliest work referenced on fiber tow steering was in 1972 [107]. Advanced Fiber Placement (AFP) is a larger category of manufacturing processes that includes fiber tow steering. Kisch states [108] that the A380 and 787 fuselages are both fabricated using AFP. Although not specifically stated, it is likely that AFP has been employed for its efficiency in fabricating large composite laminate structures and less for its ability to exploit intricate fiber orientations via fiber tow steering.

Many research efforts have involved improving the strength or buckling resistance of plates or plates with cut-outs. It has been shown that a simple "S" shaped fiber path (one that aligns axially, curves to 45°, and then realigns axially again) improves the buckling resistance of axially loaded plates by "shifting the load away from the unsupported center," [109]. With additional buckling resistance in skin panels, fewer stiffeners may be needed. When designing for fiber tow steering, practical constraints like the fiber tow turning radius must be met. The papers chosen for Table 17 are recent and cover a broad group of topics relevant to fiber tow steering, including manufacturing processes and applications. In particular, Ghiasi, et al. [110] provides a review of "variable stiffness design" in composite laminates, which includes to the use of curvilinear fiber paths. It also discusses methods for determining optimal fiber paths based on principle stresses or load paths. The paper by De Leon, et al. [35] discussed above obtains the fiber angle of each finite element, which may also be considered a type of tow steering. The last two papers in the table consider aeroelastic metrics, with Ref. [111] in particular considering flutter-based optimization of a tow-steered thin walled beam.

Table 17. Papers on fiber tow steering.

Year	[Ref] Authors (#Cited works)	Title	Emphasis
2006	[108] Kisch (10)	Automated Fiber Placement Historical Perspective	Manufacturing processes and applications
2010	[112] Ijsselmuiden, Abdalla, Gürdal (33)	Optimization of Variable-Stiffness Panels for Maximum Buckling Load Using Lamination Parameters	State-of-the-art on methods used to parameterize and optimize fiber path orientations
2009	[113] Weaver, Potter, Hazra, Saverymuthapulle, Hawthorne (30)	Buckling of Variable Angle Tow Plates: From Concept to Experiment	Optimizing for buckling resistance
2010	[114] Alhajahmad, Abdalla, Gürdal (16)	Optimal Design of Tow-Placed Fuselage Panels for Maximum Strength with Buckling Considerations	Optimizing for strength and buckling resistance
2009	[109] Butler, Baker, Liu (10)	Damage Tolerance of Buckling Optimized Variable Angle Tow Panels	Optimizing for maximum buckling resistance and analyzing for damage tolerance
2009	[115] Honda, Narita, Sasaki (20)	Maximizing the Fundamental Frequency of Laminated Composite Plates with Optimally Shaped Curvilinear Fibers	Optimizing for desired frequency
2005	[116] Tatting, Setoodeh, Gürdal (8)	Enhancements of Tow-Steering Design Techniques: Design of Rectangular Panel Under Combined Loads	Optimizing a panel for combined loads (axial and shear)
2010	[110] Ghiasi, Fayazbakhsh, Pasini, Lessard (118)	Optimum Stacking Sequence Design of Composite Materials, Part II: Variable Stiffness Design	A review paper on variable stiffness designs using curvilinear fiber paths in composite laminates
2010	[117] Lopes, Gürdal, Camanho (23)	Tailoring for Strength of Composite Steered-Fibre Panels with Cutouts	Optimizing a panel with a cutout
2011	[118] Croft, Lessard, Pasini, Hojjati, Chen, Yousefpour (26)	Experimental Study of the Effect of Automated Fiber Placement Induced Defects on Performance of Composite Laminates	Manufacturing defects pertaining to tow steering and their effect on structural performance
2012	[119] Kim, Potter, Weaver (20)	Continuous Tow Shearing For Manufacturing Variable Angle Tow Composites	Manufacturing processes to mitigate fabrication defects
2012	[111] Haddadpour, Zamani (27)	Curvilinear Fiber Optimization Tools for Aeroelastic Design of Composite Wings	Flutter optimization of a tow-steered thin walled beam

2013	[120] Stodieck, Cooper, Weaver, Kealy (39)	Improved Aeroelastic Tailoring Using Tow-Steered Composites	Parameter studies of an aeroelastic flat plate

3.1.4 Nonconventional Structural Designs

Research in lightweight structural design covers various architectures, including trusses, curvilinear stiffeners, and stiffeners/ribs of various cross-sections or topologies. As previously mentioned, new manufacturing processes, such as the electron beam freeform fabrication (EBF^3) [106], can enable the fabrication of complex lightweight structures by depositing material rather than removing bulk material. The papers in Table 18 pertain to methods or concepts for reducing weight through detailed structural arrangement; direct aerodynamic interaction is not considered in most cases.

Table 18. Papers on nonconventional structural design research.

Year	[Ref] Authors (#Cited works)	Title	Summary
1990	[121] Swanson, Gurdal, Starnes (10)	Structural Efficiency Study of Graphite-Epoxy Aircraft Rib Structures	Compared rib designs comprised of corrugated panels, hat- and blade-stiffened panels, and unstiffened flat panels using various combinations of axial compression, in-plane shear, and out-of-plane normal pressure loadings. The designs were highly dependent on the load conditions. Did not consider aerodynamics.
1994	[122] Balabanov, Haftka (15)	Topology Optimization of a Transport Wing Internal Structure	Modeled the internal structure of a wing box with a dense lattice network of beams, and used topology optimization to find the best layout.
2000	[123] Malla, Adib-Jahromi, Accorsi (37)	Passive Vibration Suppression in Truss-Type Structures with Tubular Members	Modeled a truss structure with an integrated damping element and found it difficult to characterize. Therefore they developed a tool for conducting quick parametric studies on damped truss designs. Did not consider aerodynamics.
2000	[124] Campanile, Sachau (23)	The Belt-Rib Concept: A Structronic Approach to Variable Camber	Introduces the belt-rib concept for aircraft wing ribs that allow or produce (if actuated) variable camber.
2001	[125] Eschenhauer, Olhoff (134)	Topology Optimization of Continuum Structures: a Review	Obtains the optimal topology of a rib cross-section under prescribed aerodynamic loads.
2002	[126] Krog, Tucker, Rollema (2)	Application of Topology Sizing and Shape Optimization Methods to Optimal Design of Aircraft Components	Reduces the weight in ribs using topology optimization. Explains the challenges of modeling the load and boundary conditions accurately. Did not consider aerodynamics.
2003	[127] Ragon, Gurdal, Haftka, Tzong (11)	Bilevel Design of a Wing Structure Using Response Surfaces	Proposes a technique for local size optimization of a panel stiffened with “upside down L-shaped” stiffeners. Considered weight, buckling, strength, and tip deflection. Did not consider aerodynamics.
2003	[128] Murphy, Hinkle (20)	Some Performance Trends In Hierarchical Truss Structures	Determines that trusses having truss members comprised of trusses (i.e., 2nd order hierarchy) have better performance than other orders of hierarchy under certain conditions and assumptions. Assumptions are explained in the conclusions. Did not consider aerodynamics.
2004	[129] Cadogan, Smith, Uhelsky, MacKusick (13)	Morphing Inflatable Wing Development for Compact Package Unmanned Aerial Vehicles	Discusses research on morphing inflatable wings. Proposes a concept of attaching an inflatable extension at a wing tip to increase wing aspect ratio. Describes ‘nastic’ structures which can undergo large strain while providing structural functions.

2005	[130] Bushnell, Rankin (46)	Optimum Design Of Stiffened Panels With Substiffeners	Found that adding substiffeners to panels did not reduce the weight significantly. Did not consider aerodynamics.
2005	[131] Campanile, Anders (26)	Aerodynamic and Aeroelastic Amplification in Adaptive Belt-rib Airfoils	Analyzes aeroelastic amplification to minimize the energy required to actuate the belt-rib concept. Actuation methods for the structure are not yet determined.
2006	[132] Herencia, Weaver, Friswell (42)	Local Optimisation of Long Anisotropic Laminated Fibre Composite Panels with T Shape Stiffeners	Developed a two-step local optimization routine for a composite laminate panel with T-shaped stiffeners that enabled weight reduction. Considered a combined loading case along with strength, buckling, and manufacturing constraints. Did not consider aerodynamics.
2008	[133] Bostandzhiyan, Bokov, Shteinberg (11)	Flexural Characteristics and Aerodynamic Aspects of the Design of the Bird Feather Shaft	Describes how the bending stiffness of bird feather shafts enables high angles of attack without flow separation. It also shows how the cross-section of the bird feather shaft has a unique, asymmetric branching design for beneficial response in both downward and upward flapping.
2009	[134] Cavagna, Ricci, Riccobene (38)	A Fast Tool for Structural Sizing, Aeroelastic Analysis and Optimization in Aircraft Conceptual Design	Developed an MDAO that includes weight calculation, aeroelastic analysis, and local structural sizing. Structural details such as the truss-core sandwich, unflanged integrally stiffened shell, and Z-stiffened shell are included in the optimization.
2010	[135] Dang, Kapania, Slemp, Bhatia, Gurav (16)	Optimization and Postbuckling Analysis of Curvilinear-Stiffened Panels Under Multiple Load Cases	Describes how curvilinear stiffeners reduced the weight of a panel with holes by 7% compared to using straight stiffeners. Considered buckling, damage tolerance, stress, and crippling. Did not consider aerodynamics.
2011	[136] Locatelli, Mulani, Kapania (39)	Wing-Box Weight Optimization Using Curvilinear Spars and Ribs (SpaRibs)	Describes how curvilinear stiffeners reduce the weight of wing boxes. Considered weight, buckling, and stress. Did not consider aerodynamics.
2012	[137] Ning, Pellegrino (29)	Design of Lightweight Structural Components for Direct Digital Manufacturing	Optimizes the material arrangement within a beam's cross-section for both minimum weight and maximum stiffness. Result is similar to an I-beam with most material at the top and bottom edges of the cross-section. The results show improved performance over solid beam (much improvement) and simple truss (little improvement). Did not compare to an I-beam though.
2012	[138] Oremont, Schultz (18)	An Efficient Analysis Methodology for Fluted-Core Composite Structures	Presents an efficient analysis methodology for fluted-core sandwich composite panels that can be used to guide analyses for other structural concepts.
2013	[139] Stanford, Beran (58)	Aerothermoelastic Topology Optimization with Flutter and Buckling Constraints	Optimizes the internal topology of a sandwich panel structure exposed to high-speed, high-temperature flow over its upper surface. Showed substantial improvements in unheated flutter boundaries, thermal buckling, and heated flutter boundaries.

3.2 Active

The benefits of aeroelastic tailoring can also be achieved through active means. For example, conventional materials and structures can be replaced with smart materials and structures whose properties or configurations change in response to external stimuli. Control effectors that directly interact with the air flow, such as control surfaces, can also be utilized for aeroelastic tailoring. Two examples of this are found in Zeiler and Weisshaar [140] and Weisshaar and Duke [18]. Table 19 includes survey papers on smart materials/structures and their application in aeronautics. In particular, Barbarino, et al. [10] are extremely thorough in their review of morphing aircraft and include a pictorial timeline of the morphing aircraft since the Wright Flyer, which includes the Mission Adaptive Wing of 1985, the Active Aeroelastic Wing of 2002, and numerous wings from university based research programs.

Table 20 and Table 21 provide more detailed examples of smart structures and smart materials research in aircraft wing design, respectively. Despite the research invested in smart materials, Fontanazza, et al. [141] claim "the capability of current smart materials is relatively limited. Hence their use for morphing has mainly been applied to micro UAVs, which are subject to smaller wing loads and are easier and cheaper to flight test than traditional aircrafts." Examples of smart materials application on the smaller scale are found in papers by Barret [142], Lim et al., [143], Vos et al., [144], and Stanford et al., [145]. Kornbluh, et al. [146] provides a thorough table of smart materials and their properties shown in Table 22 (many of these materials are also compared to one another in Figure 2).

The materials in Table 22 are broken down into two categories "(1) materials whose intrinsic mechanical properties can be controlled, such as by the application of an electromagnetic field or thermal control, and (2) active materials that function as actuators and generators in adding to or subtracting from the elastic and viscous (damping) energy of deformation of the material and thereby effectively modulating the viscoelastic properties," [146]. They add that "Each of these [smart] materials is suitable for some applications, but no single technology is capable of fast and efficient response that can produce a very wide range of stiffness and damping with a high elongation capability, that is, go from rubber to rigid." For this reason, Kornbluh et al. [146] suggest configuring materials, structures, and mechanisms on the meso-scale to fabricate desired structural properties since "advances in micro- and nano-scale fabrication technologies could begin to allow us to make these meso-scale composite materials appear as true active materials."

Table 23 provides some examples of how the integration of materials and mechanisms can achieve a more desirable material or structural response. One of these examples is fluid flexible matrix composites (F2MC), which can be tailored to meet any of the properties depicted as open circles in Figure 2 (taken from Shan et al., [147]).

Table 19. Survey papers on smart materials and structures that include aeronautical applications.

Year	[Ref] Authors (#Cited works)	Title
2000	[148] Giurgiutiu (65)	Active-Materials Induced-Strain Actuation for Aeroelastic Vibration Control
2004	[146] Kornbluh, Prahlad, Pelrine, Stanford, Rosenthal, von Guggenberg (35)	Rubber to Rigid, Clamped to Undamped: Toward Composite Materials with Wide-Range Controllable Stiffness and Damping
2006	[141] Fontanazza, Talling, Jackson, Dashwood, Dye, Iannucci (38)	Morphing Wing Technologies Research
2007	[149] Njuguna (160)	Flutter Prediction, Suppression and Control in Aircraft Composite Wings as a Design Prerequisite: A Survey
2011	[10] Barbarino, Bilgen, Ajaj, Friswell, Inman (342)	A Review of Morphing Aircraft

Table 20. Papers on structures designed to actively change wing stiffness, camber, and twist.

Year	[Ref] Authors (#Cited works)	Title	Overview
2002	[150] Khot, Zweber, Veley, Oz, Eastep (7)	Flexible Composite Wing with Internal Actuation for Roll Maneuver	Developed a wing model that is actuated by antagonistic axial forces near the root to induce twist without ailerons.
2003	[151] Kota, Hetrick, Osborn, Paul, Pendleton, Flick, Tilmann (14)	Design and Application of Compliant Mechanisms for Morphing Aircraft Structures	Developed conformable leading and trailing edge flaps.

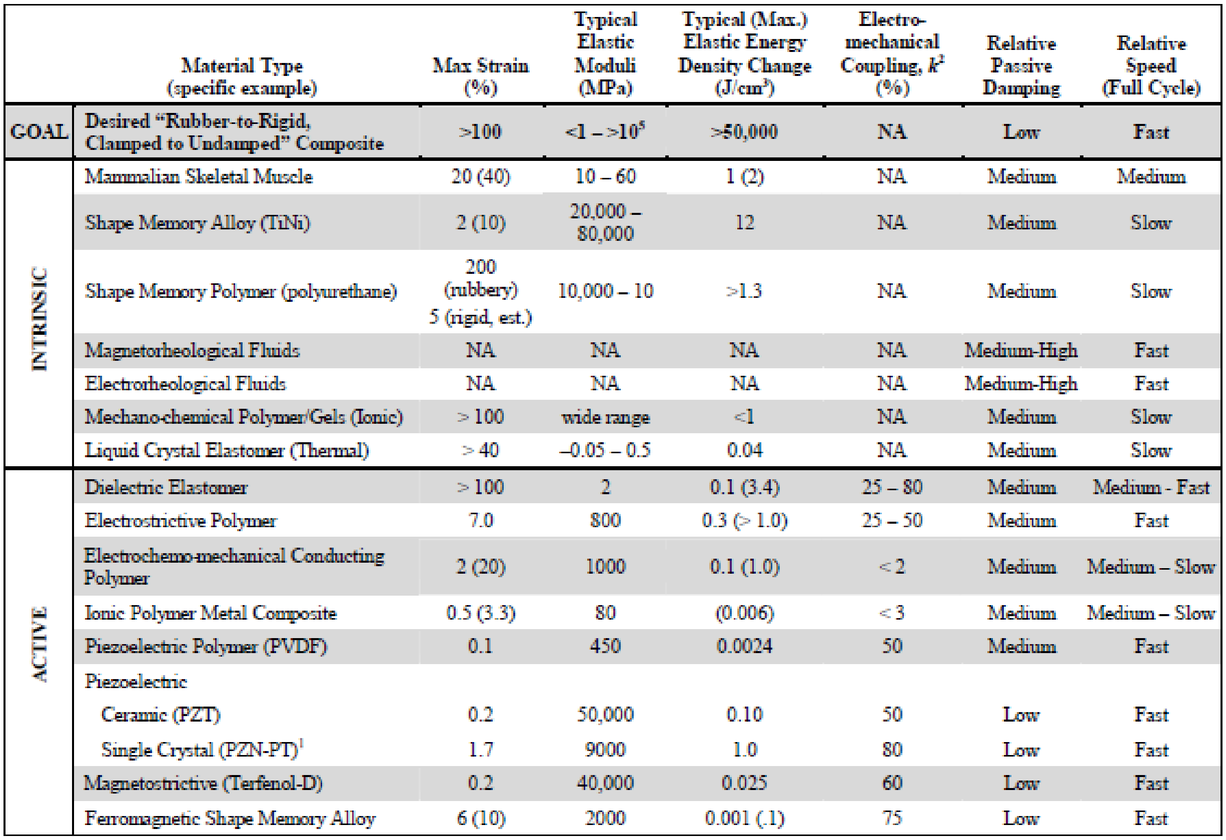
2003	[152] Zink, Raveh, Mavris (28)	Integrated Trim and Structural Design Process for Active Aeroelastic Wing Technology	Integrated active aeroelastic wing design process via ASTROS, with gear ratio and structural design variables.
2004	[153] Chen, Sarhaddi, Jha, Liu, Griffin, Yurkovich (16)	Variable Stiffness Spar Approach for Aircraft Maneuver Enhancement Using ASTROS	Developed a variable stiffness spar, a "segmented spar having articulated joints at the connections with wing ribs and an electrical actuator capable of rotating the spar" for the F/A-18 pre-roll-modification aircraft model. Showed improvement in roll rate while satisfying deflection, flutter, and hinge moment constraints.
2006	[154] Cooper (12)	Adaptive Stiffness Structures for Air Vehicle Drag Reduction	Developed demonstrative prototypes of wings of variable stiffness due to rotatable spars and movable spars in the chordwise direction. Still need to determine if the concept is scalable to larger aircraft.
2006	[155] Maute, Reich (51)	Integrated Multidisciplinary Topology Optimization Approach to Adaptive Wing Design	Used topology optimization to determine the best arrangement of material, actuators, and pivot points within a wing's cross-section to achieve desired external shape change. Couples an Euler CFD solver to a finite element method.

Table 21. Papers that incorporate SMAs or piezoelectrics in wing design.

Year	[Ref] Authors (#Cited works)	Title	Overview
1993	[156] Ehlers, Weisshaar (25)	Static Aeroelastic Control of an Adaptive Lifting Surface	Developed a non-dimensionalized laminated composite aeroelastic beam model having embedded piezoelectric actuators. Studied lift and lift effectiveness. Concluded that "strength parameters indicate that available materials may fall short of the demands that are placed upon them" and that "available actuator strength is inversely proportional to the wing loading *W/S*."
1996	[157] Nam, Kim, Weisshaar (25)	Optimal Sizing and Placement of Piezo-Actuators for Active Flutter Suppression	Optimized the thickness, location, and size of piezo-actuators on a non-dimensionalized composite plate wing model. Determined that flutter speed could be increased.
2000	[158] Cesnik, Ortega-Morales, Patil (41)	Active Aeroelastic Tailoring of High Aspect Ratio Composite Wings	Developed a composite wing model with embedded piezoelectric strain actuators at the wind tunnel scale. Determined optimal actuator configurations for gust load alleviation, increased stability, and a combination of both objectives.
2001	[159] Forster, Livne (21)	Integrated Structure/Actuation Synthesis of Strain Actuated Devices for Shape Control	Developed an approach for synthesizing devices for shape control using strain actuated devices. Did not account for aerodynamic loads.
2002	[160] Nam, Chattopadhyay, Kim (21)	Application of Shape Memory Alloy (SMA) Spars for Aircraft Maneuver Enhancement	Modified an F-16 wing model to have two spars made of SMA material. Showed an increase in roll effectiveness.
2004	[161] Kudva (15)	Overview of the DARPA Smart Wing Project	Demonstrated various benefits to actuating conformable leading and trailing edge surfaces with smart materials through several wind tunnel tests. Piezoelectric motors showed better performance over the SMA actuators.

2004	[162] Bartley-Cho, Wang, Martin, Kudva, West (11)	Development of High-rate, Adaptive Trailing Edge Control Surface for the Smart Wing Phase 2 Wind Tunnel Model	Explains the various design concepts considered for the Smart Wing wind tunnel models with emphasis on the actuator and conformable control surface options. Describes the final designs in detail.

Table 22. Comparison of smart materials by their properties (from Ref. [146]).



	Material Type (specific example)	Max Strain (%)	Typical Elastic Moduli (MPa)	Typical (Max.) Elastic Energy Density Change (J/cm^3)	Electro-mechanical Coupling, k^2 (%)	Relative Passive Damping	Relative Speed (Full Cycle)
GOAL	**Desired "Rubber-to-Rigid, Clamped to Undamped" Composite**	**>100**	**<1 – >10^5**	**>50,000**	**NA**	**Low**	**Fast**
INTRINSIC	Mammalian Skeletal Muscle	20 (40)	10 – 60	1 (2)	NA	Medium	Medium
	Shape Memory Alloy (TiNi)	2 (10)	20,000 – 80,000	12	NA	Medium	Slow
	Shape Memory Polymer (polyurethane)	200 (rubbery) 5 (rigid, est.)	10,000 – 10	>1.3	NA	Medium	Slow
	Magnetorheological Fluids	NA	NA	NA	NA	Medium-High	Fast
	Electrorheological Fluids	NA	NA	NA	NA	Medium-High	Fast
	Mechano-chemical Polymer/Gels (Ionic)	> 100	wide range	<1	NA	Medium	Slow
	Liquid Crystal Elastomer (Thermal)	> 40	–0.05 – 0.5	0.04	NA	Medium	Slow
ACTIVE	Dielectric Elastomer	> 100	2	0.1 (3.4)	25 – 80	Medium	Medium - Fast
	Electrostrictive Polymer	7.0	800	0.3 (> 1.0)	25 – 50	Medium	Fast
	Electrochemo-mechanical Conducting Polymer	2 (20)	1000	0.1 (1.0)	< 2	Medium	Medium – Slow
	Ionic Polymer Metal Composite	0.5 (3.3)	80	(0.006)	< 3	Medium	Medium – Slow
	Piezoelectric Polymer (PVDF)	0.1	450	0.0024	50	Medium	Fast
	Piezoelectric						
	Ceramic (PZT)	0.2	50,000	0.10	50	Low	Fast
	Single Crystal (PZN-PT)[1]	1.7	9000	1.0	80	Low	Fast
	Magnetostrictive (Terfenol-D)	0.2	40,000	0.025	60	Low	Fast
	Ferromagnetic Shape Memory Alloy	6 (10)	2000	0.001 (.1)	75	Low	Fast

Table 23. Papers on systems that manipulate the output of smart materials to achieve additional performance.

Year	[Ref] Authors (#Cited works)	Title	Overview
2008	[163] Sofla, Elzey, Wadley (32)	Two-way Antagonistic Shape Actuation Based on the One-way Shape Memory Effect	Creates a two-way flexural actuator from combining a mechanism with (one-way) SMA actuators
2009	[164] Philen, Phillips, Baur (30)	Variable Modulus Materials based upon F2MC Reinforced Shape Memory Polymers	Creates a highly variable modulus material by integrating 'flexible matrix composite tubes having an active fluid-filling function' into shape memory polymers, both of which already have variable modulus capabilities

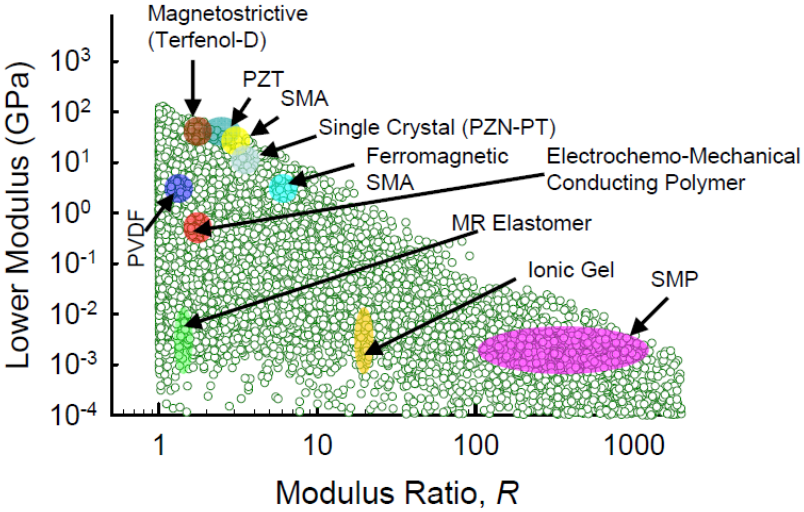


Figure 2. A comparison of smart materials based on their variable modulus capabilities. The open circles represent various F2MC configurations (from Ref. [147]).

4 Conclusions

Much of the applied aeroelastic tailoring work in aircraft wings has taken a more “global” approach by exploiting a single laminate orientation parameter within the wing skin. However, with newer manufacturing processes such as fiber tow steering and EBF^3, researchers have begun to focus their design efforts more locally along the wing with favorable results. Nonetheless, the greatest challenge is designing a high performance, lightweight wing that accounts for *all* factors encountered in flight. Many of the paper studies described above either simplify or ignore constraints to lessen the design problem’s complexity. For this reason, in at least one instance above, the outcomes of two papers somewhat contradict one another. Guo et al. [36] and Bohlmann and Scott [52] both discovered the various benefits of [-45/45]° ply orientations with respect to aeroelastic tailoring , but only Bohlmann and Scott accounted for strength, and realized that particular design had a weight penalty. As always, caution must be taken before directly applying the result of a research effort. In addition to aeroelastic tailoring approaches, numerous potentially enabling technologies are being studied today. Further research into these new capabilities may substantially deviate from the typical approach to aeroelastic tailoring and reveal game changers of either an active or passive nature.

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14. ABSTRACT

This paper provides a brief overview of the state-of-the-art for aeroelastic tailoring of subsonic transport aircraft and offers additional resources on related research efforts. Emphasis is placed on aircraft having straight or aft swept wings. The literature covers computational synthesis tools developed for aeroelastic tailoring and numerous design studies focused on discovering new methods for passive aeroelastic control. Several new structural and material technologies are presented as potential enablers of aeroelastic tailoring, including selectively reinforced materials, functionally graded materials, fiber tow steered composite laminates, and various nonconventional structural designs. In addition, smart materials and structures whose properties or configurations change in response to external stimuli are presented as potential active approaches to aeroelastic tailoring.

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