ACTIVE AND PASSIVE STRUCTURAL MEASURES FOR AEROELASTIC WINGLET DESIGN

Björn Nagel*, Markus Kintscher, Thomas Streit*****
***German Aerospace Center, Inst. of Air Transport System and Technology Assessment**
****German Aerospace Center, Inst. of Composite Structures and Adaptive Systems**
*****German Aerospace Center, Inst. of Aerodynamics and Flow Technology**

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Abstract

This paper concerns the aero-structural design of winglets for transport aircrafts. The different multidisciplinary design targets are discussed and limitations of the conventionally aerodynamics-focused design approach are shown. In order to better combine conflictive targets the design space is opened towards advanced passive and active structural concepts. As basis, the suitability of different state-of-the-art numerical measures is evaluated and tools engineered for the efficient investigation of unconventional structures are presented.

1 Introduction

The aeronautical industry is facing severe economic and ecologic challenges. A significant enhancement of efficiency is imperative and has to be introduced into the transport system soon. Aerodynamic wing tip devices such as winglets are used for drag reduction and offer the opportunity to be also retrofit to the existing fleet. But especially the integration into an existing design constitutes a challenging, multidisciplinary task.

Aiming at maximized lift-over-drag in cruise flight winglets are designed to reduce the induced drag. Nevertheless, special attention has to be paid to the shaping of the intersection between wing and winglet to avoid undesirable transonic effects caused by the convex geometry.

In the design of wings aerodynamic efficiency has always to be traded against structural sizing loads. The optimal aero-structural compromise is gained at spanwise lift distribution being closer to linear than to the elliptic distribution. However, retrofit design has to take additional account for a certain wing root bending moment reserve of the reference wing [15].

In particular, aerodynamically efficient wings are of high aspect-ratio and hence show significant aeroelastic interactions resulting in varying states of equilibrium during the cruise flight range. The large sensivity of drag and wing root bending moment to twist is underlined for configurations with large wing tip devices compared to clean wings, whereat also the importance of viscous effects is emphasized [11].

Thus, retrofit design of winglets has to compromise between induced and transonic drag while taking account for structural strength of the basis wing and considering varying aeroelastic interactions. This task is getting even more relevant if further drag reduction based on delay of laminar-turbulent transition is comprised [1].

Since winglets aim at drag reduction whereat higher order aerodynamic effects play a dominant role, state-of-the-art design is usually characterized by an aerodynamic point of view. Conventionally, only the outer shape is subject of optimization. The inner structure is usually considered to be conventionally designed making aeroelastic interactions a function of the shape only. To some extent elaborate shaping can combine the different targets. But the potential of continuous adaptation based on tailored structures or even active structures [31] is not exploited.

This paper discusses structural concepts based on fiber reinforced composite materials which are appropriate to introduce more degrees of freedom into winglet design aiming at quasi-static effects and the required numerical measures. The extended design space permits a better adaptation to the different conditions during cruise flight. Beyond passive structural tailoring also active components are considered. Additional to the described targets active shape control winglets can be used for the active reduction of wake vortices enabling flight in closer staggering in the vicinity of airports [17], [12].

2 State-of-the-art numerical measures for structural design in multidisciplinary environments

In the early stages of interdisciplinary wing design beam models constitute reasonable physics based approaches for conventional configurations. Also fiber reinforced composite materials with their laminate lay-up dependant anisotropic stiffness properties can be included for the investigation of quasi-static aerolastic tailoring [5] or the optimization for dynamic aeroelastic properties [8], [9].

Advanced structural concepts can be treated by adaptation and extension of the analytical models. Examples are e.g. the optimization of wings using aeroelastic tailoring and adaptive control surfaces [34], the optimization of active aeroelastic wings considering structural nonlinearities and maneuver load inaccuracies [37] or the aeroelastic optimization incorporating active materials [4].

Studies on pre-design level usually make use of elementary aerodynamic models which base on the potential theory. Thus, transonic effects, which play a dominant role for cruise flight efficiency, can not be accounted for. Hence, with increasing computing power higher fidelity aerodynamic measures are becoming state-of-the-art in aeroelastic analysis and optimization [10], [11], [15].

For clean wing configurations, the calculation of displacements can be realized satisfactorily using beam models. But a mandatory precondition for elastic calculations is the determination of the stiffness which directly results from structural sizing.

Kinematic assumptions, which are fundamental to beam models, significantly restrain the solution space in terms of strain components in the plane of the skin and the derived stress components. This inaccuracy has a tolerable impact on the sizing of metallic structures where equivalent stress, which smears the stress components, is widely used. But the design of composite materials relies stronger on the individual stress components and thus may suffer significant deviations in stiffness and mass if it is based on beam models [35]. Besides the specific requirements of composite materials also the shape of wing tip devices can infringe upon the fundamental geometric assumptions of beam models.

A better representation of physics can be introduced into structural design by the utilization of Finite Element Methods (FEM) based on the shell theory. But the more direct calculation of strains and higher versatility of geometries have to be bought for the effort in explicit modeling.

Automated model generators and optimization routines are the key enablers for the use of FEM in pre-design [24]. Based on central geometry engines also higher fidelity aerodynamic models can be automatically generated to some extent. In combination with an optimizer medium-fidelity MDO processes can be realized, whereat often a central optimization scheme is used [19].

This approach which is dedicated to Knowledge Based Engineering (KBE) is also employed for design considering other disciplines such as vibro-acoustics. Innovative structural concepts including active components can be included into the central modeling engine [33]. But investigating multiple novel structural concepts emphasizes the effort of creating prototype components for the model generators.

In particular if disciplinary detailed knowledge is required, e.g. at the application of tailored composite structures or at the investigation of transonic aerodynamics, the multidisciplinary design process can not be handled by one person alone but collaboration of different experts is mandatory. In this case, the standardized architecture of such centralized approaches is likely to corrupt preferences and standards of disciplinary researchers. Furthermore, the integration of external models e.g. in course of collaborative research might cause high effort although in theory standardized interfaces such as IGES should enable problem-free model interchange.

The following paragraphs present a numeric approach for automated modeling and sizing of advanced structures appropriate for composite materials and capable of handling non-beam-like geometries such as winglets. The tools are programmed aiming at easy adaptability to novel technologies and at versatile and stable integration into different analysis and design environments.

3 Structural modeling

Structural design in an aeroelastic environment is an iterative process and consists of the three steps model generation, calculation of aerodynamic loads and structural sizing.

FEM-shell modeling bases on explicit three dimensional geometries. A popular approach is parametric Computer Aided Design (CAD) and subsequent meshing making use of commercial software [33]. In a static, homogeneous tool environment this approach offers a series of advantages. But if geometries from other sources have to be imported or one of the commercial codes is varied e.g. due to a version update excessive conversions or adaptations may follow.

Not at least due to the prevailing transonic effects aerodynamic design is very sensitive and an early introduction of high fidelity CFD measures is reasonable. Thus, it can be assumed that an aerodynamic surface discretization is already available when the structural model has to be generated. This surface description can be exported by probably all Computational Fluid Dynamics (CFD) tools to ASCII files containing the list with mesh points and, in case of unstructured CFD grids, the connectivity. This versatile surface description constitutes a robust basis for the FEM model generator PARA_MAM [23].

PARA_MAM (Parametric, Simple and fast Mesh Based Aircraft Modeling Tool) is a suite of MATLAB macros which calculates the 3D geometric key-points of the structural model from the mentioned surface tessellation and a fully parametric description of the inner structural components. The output is a file with commands for pre-processors such as ANSYS */prep7* which generate the entire FEM model based on the pre-calculated key-points. This approach permits a bottom-up modeling concept requiring a very low number of different commands only. Hence, translating the output to syntaxes of other preprocessors is straight forward. Since complex and error-prone operations such as Booleans are avoided, the tool works very stable and thus is well suited to be used within MDO loops.

Geometric key-points are the intersections of ribs and spars which can be calculated 2D in the planform of the wing easily. The core of PARA_MAM is the calculation of the 3D key-points which are constituted by the penetration points of the rib-spar intersection lines with the aerodynamic hull. The projection of the 2D key-points to the chord is the basis of the rib-spar intersection lines whose inclination angles are specified in the input file via the variable distribution of inclination angles of ribs and spars. The penetration points are searched using an efficient ray-tracing scheme making this model generator competitive to CAD based approaches also in speed [28].

With the known 3D intersections the skin and potentially intersecting and branching ribs and spars are created by linking of key points. A higher resolution of the geometry can be achieved by the introduction of additional virtual spars and ribs. Further structural elements such as explicit stringers or engines and pylons are modularly added as prototypes referring to the geometric key-points.

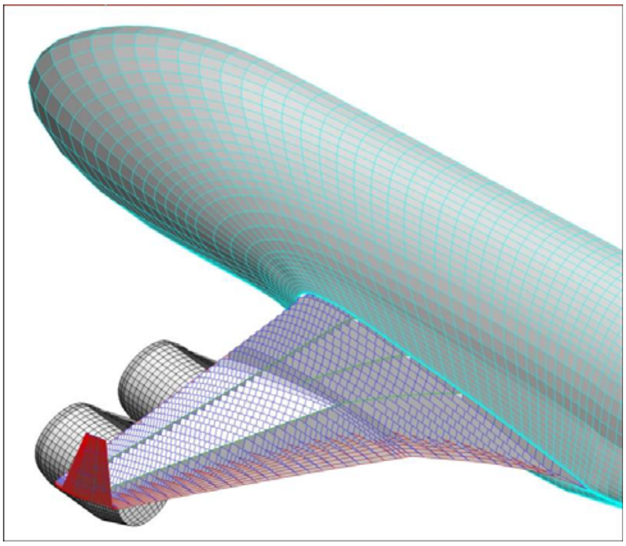

Figure 1: PARA_MAM FEM wing-winglet model with engine dummies and CFD surface mesh of the fuselage.

4 Aero-structural interactions

For aerodynamic calculations the DLR RANS solvers FLOWer for structured and TAU for unstructured grids are used. They enable reliable drag predication and realistic pressure distributions for structural sizing.

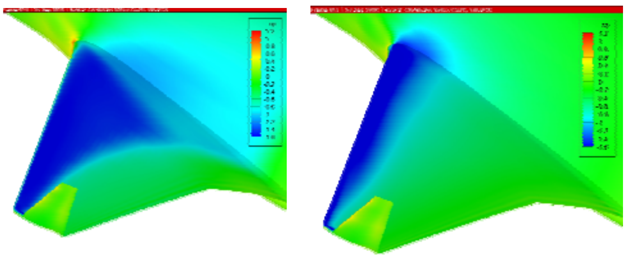

Figure 2: 2,5g load case pressure distribution in a gust in cruise flight conditions and at sea level after pull out of a dive.

The here discussed quasi-static aeroelastic interactions can be treated using a sequential coupling scheme as displayed in Figure 3. A loose coupling is established between two conventional analysis codes by over-cross interpolation of input and output data: After the initial aerodynamic calculation the pressure is available at the aerodynamic grid points. Its transfer to the nodes of the structural model is realized using an interpolation scheme based on radial basis functions. The nodal forces are input to a structural FEM analysis which results in a displacement vector field for the structural nodes. They are interpolated back to the surface grid points of the CFD model which is then deformed to the calculated new shape. This process is repeated till convergence is reached [13].

All input and output data of the interpolation routine is provided in ASCII files. The contained information uses the AMIF format which designates data as grid points, connectivity, pressure, force or displacement component at a specified point. Interfaces for this simple and versatile format can probably be created for all relevant FEM and CFD codes without a high effort. Thus, this coupling scheme constitutes a robust and versatile link between structures and aerodynamics.

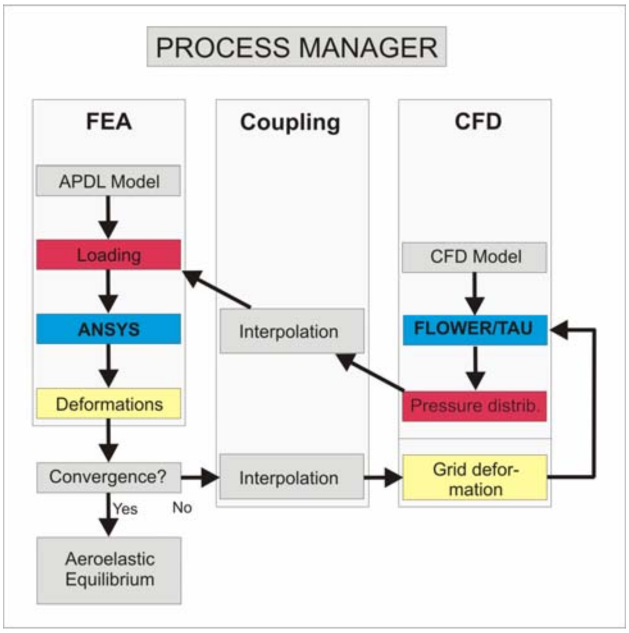

Figure 3: Sequential FEM-CFD coupling

5 Structural sizing

FEM shell models of wings typically consist of more than 10.000 elements. Each of the elements can be initialized with material properties representing an arbitrary laminate lay-up. Thus, although considering a fixed topology the optimization problem contains several ten thousands of design variables.

One approach to handle the problem is breaking the structure down to few design regions within which all elements share the same properties. Like this, the structural sizing can be controlled by an external optimizer using the individual exploitation of material's strength in the design regions or by use of an even more concentrated structural measure such as the Kreiselmeier Steinhäuser function. This concept is able to exploit the potential of mature optimization tools. However, the remaining solution space can not exploit the light weight potential of fiber composite materials since this would require a distributed design accounting for local load vectors within the design regions.

Another approach to overcome the huge number of design variables is decomposition of the one optimization problem into multiple sizing problems. This strategy is fundamental to the program S_BOT (Sizing Robot). S_BOT is scripted in the ANSYS Parametric Design Language (APDL) and is an open framework of modules for automated analysis and sizing of Finite Element models [22].

For the design of wing-type structures a finite shell element model and a set of aerodynamic loads, which are kept constant during the sizing process, have to be specified. The utilization of PARA_MAM models and AMIF load files permits some simplifications in the S_BOT setup but is not mandatory. In the beginning of the process an initialization re-organizes the model in order to align each element with an individual set of properties which, in this step, equals the original properties but will later be optimized independently. Furthermore, matrix variables are created to store model properties and analysis results for the sizing process.

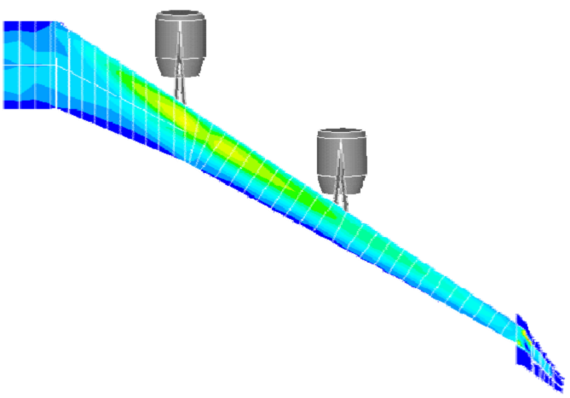

Figure 4: Skin thickness distribution

The process begins with the automated analysis of all specified load cases. Typical are at least a 2,5g pull up, a 1 g fatigue and a touch down scenario. For the design of winglets additionally yaw load cases and, if shape control during cruise range is of concern, additional 1 g off design conditions have to be considered. The analysis results of each element and each of its (composite) layers is stored in the matrix variables.

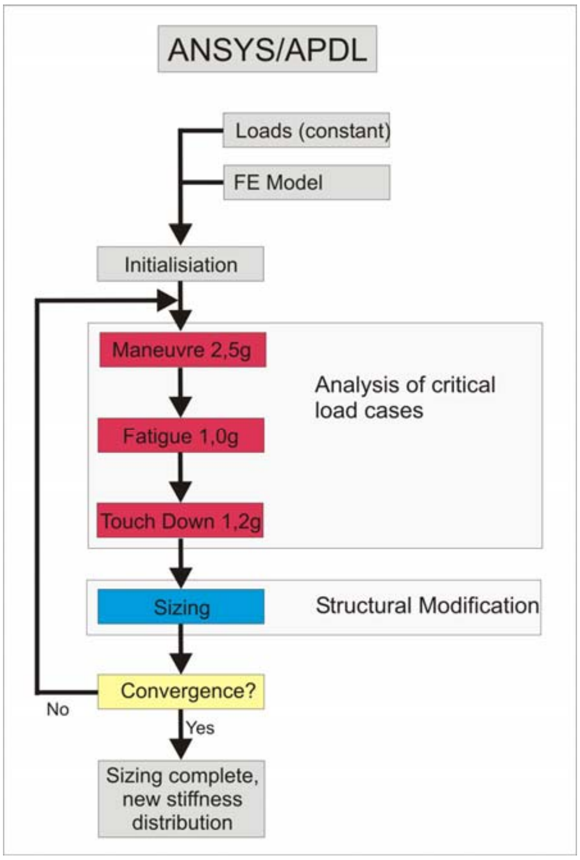

Figure 5: S_BOT flowchart

The sizing process is completely realized as set of elementary matrix operations within S_BOT. The state-of-the-art for metallic structures for example is the fully stressed design approach. For each load case the material utilization is calculated by comparison of calculated stress with the dedicated allowable stress. Metallic structures often are treated considering maximum stress components and equivalent stress levels. The maximum utilization among all load cases is then used to estimate that skin thicknesses leading to full exploitation of the materials strength; thus after sizing there is for each part of the structure one load case which leads to a full exploitation of the material limits. At the end of sizing the Finite Element model is updated to the new properties stored in the results matrices of the process. Since stress levels depend on both external loads and structural stiffness, the process has to be run iteratively till convergence. Structural sizing and aeroelastic calculation of loads and drag alternate in an outer iteration loop.

Since all model properties and all analysis results are stored in open variables, the introduction of novel sizing rules requires their formulation in elementary matrix operations only. The modular programming and coherent syntax of APDL permit an easy scripting, usually limited to a few lines of code. Although the numerical handling is simple, elaborate strategies can be implemented acting individually on elements and subsequent layers and making use of local stress and strain vectors.

Although there is almost no numerical limitation how to combine stress and strain vectors into sizing rules, strength prediction of composite material is currently one of the most critical aspect of aeroelastic design. During the World Wide Failure Exercise (WWFE) the most reliable failure criterions were evaluated for numeric failure prediction [30]. In comparison with physical tests the criterion of Puck [27] lead to the most reliable results for inter-fiber failure mode which is of special concern as described later. This criterion is implemented in S_BOT as standard for composite materials.

6 Passive structural concepts for shape control

Fundamental to light weight design is the exploitation of the materials' strength potential. In terms of fiber composites this means striving towards laminates with fibers being oriented in line with principle loads. This minimizes shear stress which would be critical to the significantly weaker matrix material and which would cause inter-fiber failure. Optimized solutions can be achieved by element-wise orientation of orthotropic materials such as unidirectional layers with stress vectors which adopts the mechanism of growing of trees [7]. This technique has been investigated mainly on panel level using Finite Element measures, whereas also nonlinear effects [36] and shell-substructure combinations [14] have been considered. A major issue of load steered composites is accounting for manufacturing procedures and the implied restriction of the fiber arrangement.

Beyond targeting weight minimization only, also shapes of the loaded structure can be subject of optimization. This technique, designated elastic tailoring, usually has been investigated equivalent to load steered composites on panel level [32]. But the most popular application is aeroelastic tailoring aiming at the design of flying shapes of wings under aerodynamic loads. The underlying principle is the initiation of shear strain and necessarily stress in the skin of the bearing box structures. Thus, elastic tailoring bases on the initiation of stress components which need to be minimized for minimum mass design and therefore necessarily deviates from the light weight optimized solution. Nevertheless, mass reduction can be gained if resulting aeroelastic shapes of equilibrium imply reduced sizing loads. Furthermore, the efficiency of elastic tailoring relies in the same way on the local orientation of fibers like load steered structures.

The structure of S_BOT is designed to support investigations on different sizing strategies trading targets of light weight against desired deflections. Figures 6 and 7 illustrate the coherences for the winglet of a large transportation aircraft. Displayed are the results of the variation of the orientation of an orthotropic composite material and the impact on the mass and twist for one constant load case. The different graphs show the difference between metallic structures and composite materials being sized using the Puck and the Max Strain failure criterion.

Tailored structures offer high potential if the design has to be made for characteristic load paths resulting in nonisotropic material properties. But if multiple load cases with variable load paths have to be considered light weight design converges more and more to isotropic material properties and the remaining nonisotropic properties my cause undesirable deflections for some load cases.

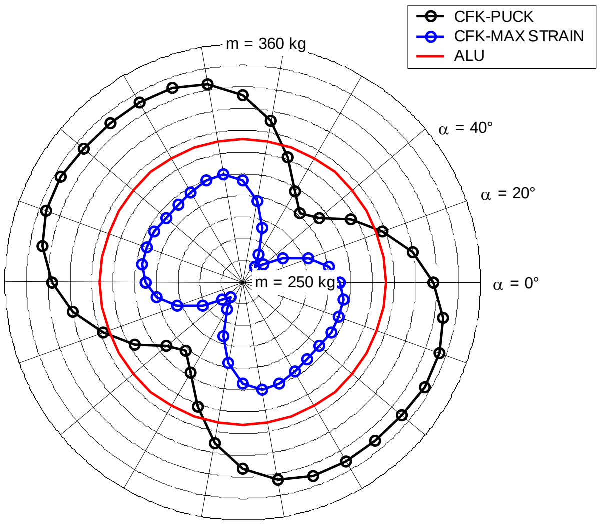

Figure 6: Mass of the winglet in relation to material orientation

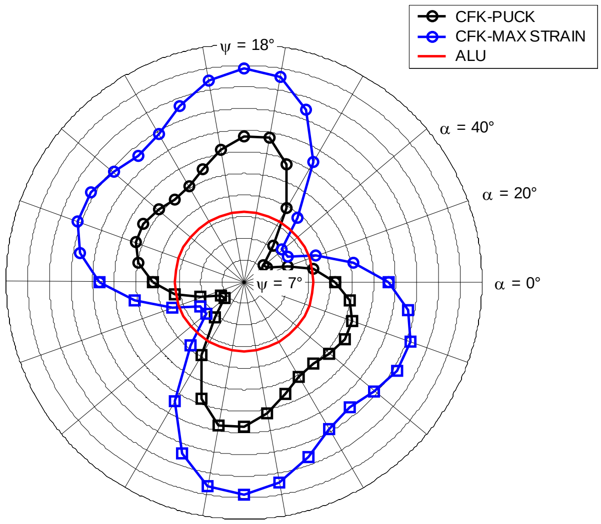

Figure 7: Twist of the winglet in relation to material orientation

7 Conventional concepts for active shape control

Several applications such as active wake vortex reduction require an active control of shape. In many cases conventional camber tabs constitute excellent solutions which can be created by FEM model generators. Figure 8 shows a PARA_MAM generated winglet model with a tab in deflected position. The attachment to the wing and the actuator are realized by link elements whereat the hydraulic actuator is equivalently activated by thermal expansion.

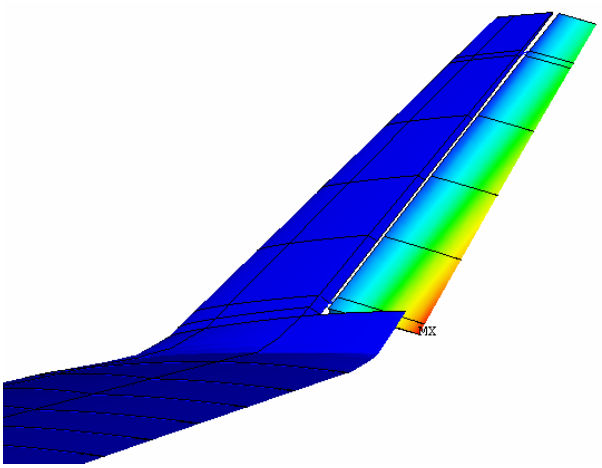

Figure 8: FEM model of winglet with deflected tab

The aerodynamic efficiency of structural shape control can be quantified using the described aeroelastic process chain if the thermal activation of the tab actuator is stepped up after achieving aeroelastic equilibrium. The impact of tab deflection in the design flying shape is obtained if the aerodynamic loads are scaled to zero in the process's structural analysis. Figure 9 displays a reduction of total drag during the downward deflection of the winglet starting from the design flying shape for Ma .83 (red) and Ma .85 (blue). The here seen drag reduction potential originates from a former optimization for a target function balancing drag and root bending moment.

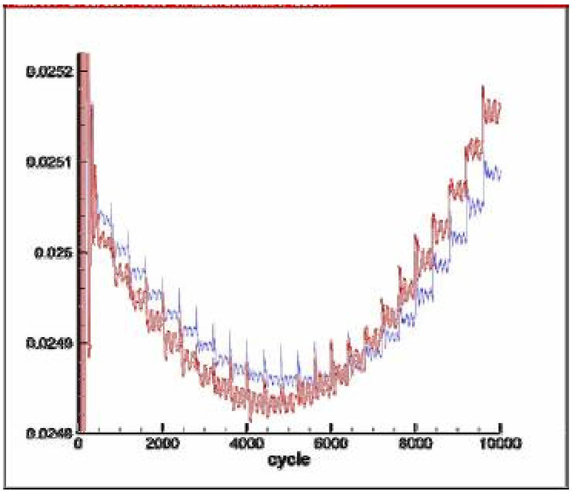

Figure 9: Over all drag during tab deflection calculated using the aeroelastic process chain

8 Innovative concepts for active shape control

The integration of conventional camber tabs means decomposing the clean wing into multiple bodies being interconnected via discrete joints. Thus, the natural loads paths of the clean wing have to be redirected and concentrated leading to a mass penalty. Multiple design concepts have been investigated for enhanced shape control targeting mass reduction and increased aerodynamic efficiency of the deformed shapes. The Horn concept [21] and the Finger concept [20] are two examples for efficient drive mechanisms enabling so called adaptive wings. A related operational system which emphasizes aerodynamic performance is the variable camber wing of the F111 [29].

Further improvements are achievable if conventional joint mechanisms can be replaced by compliant structures [25]. This is possible for joints of limited deformation requirements and offers advantages in mass and maintenance effort. One example of a discrete substructure solution considering aeroelastic interactions is the Belt-Rib concept [3]. A continuous optimization of material properties has been investigated in [38].

Beyond conventional actuators such as hydraulic actuators also multifunctional materials such as piezoelectric ceramics (PZT) or Shape Memory Alloys (SMA) might be considered although their technological readiness level still makes substantial research and development necessary. They can directly be integrated into the composite material [6] offering the potential to eliminate the entire support structure. However, the introduction of active layers into the laminate may reduce the composite’s strength potential [26]. Active deformations can be designed using selective deformable substructures [18] or elastically tailored composites [22]. Figure 10 shows the correlation between the tip deflection of a winglet and the orientation of an SMA activated orthotropic material.

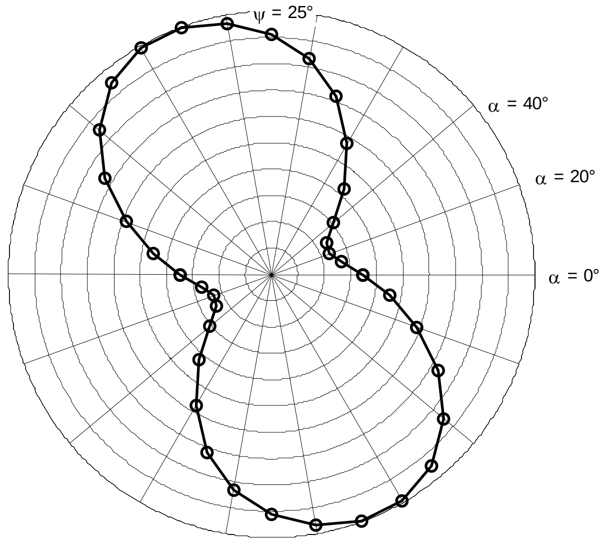

Figure 10: Twist of a winglet correlated to the orientation of a SMA actuated orthotropic composite material

Thus, multiple structural concepts are available to actively or passively adapt the shape to variable requirements. Their utilization in winglet design aiming at drag reduction is promising but appropriate numerical measures are mandatory for reliable trading of aerodynamic effectiveness against additional mass, complexity and energy consumption of active solutions. Especially investigating innovative structural concepts makes the generation of novel models and sizing strategies necessary which causes a high effort also with typical FEM model generators and optimizers. The briefly introduced tools PARA_MAM and S_BOT are designed to minimize this effort.

9 Conclusion

The design of winglets constitutes a challenging, multidisciplinary task. Today aeroelastic interactions are analyzed but optimization usually concentrates on the aerodynamic shape. Based on this design space multi criterion design is possible but adaptation to the different targets can only be realized to some extent.

Multiple structural concepts for passive and active shape control were presented which expand the design space and permit better integration of conflictive targets. But in any way adaptability has to be traded against additional mass and complexity.

In this context, reliable structural sizing requires appropriate numerical measures. Tools for Finite Element modeling and sizing were presented which are engineered for a fast and simple integration of unconventional structural designs and sizing strategies. The versatile and robust interfaces to multidisciplinary environments permit easy integration of structural experts and tools into the by now usually aerodynamics driven design process.

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