INTEGRATED DESIGN OF SMART COMPOSITES APPLIED TO SMART WINGLETS

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Abstract

Smart Structures is a technology which is demanded in European and U.S. aeronautic research agendas. The largest benefit for commercial transportation aircrafts might be more the light weight compatible simplification of systems than further increase of performance by hard-to-realise large scale shape adaption. A major challenge with morphing wings is the combination of high elasticity for efficient activation with strength and stiffness requirements from elementary wing design. This paper proposes to use the synergetic combination of smart structures and structural tailoring technique, called smart tailoring. Designing distributed anisotropic properties of passive and active composites has the potential to enable moderate shape control of conventionally designed structures providing minimum mass and complexity. A numeric procedure is presented capable to cope with the requirements of transsonic aerodynamics coupled with anisotropic composite structures. Intermediate results from ongoing research at DLR regarding multidisciplinary design and optimisation of active composites are presented.

1 Adaptive Wings

From the pioneering days of human flight on, technologies have been developed for adapting aircraft wings to aerodynamic needs. Shape control aiming at flight performance and aircraft control was usually based on mechanical gear mechanisms and exploitation of what we call today *classical engineering*. More than a century of technical evolution has led to today's transportation aircrafts with impressing flight performance and handling qualities. But the price is wings consisting of multiple mechanical bodies which are connected via discrete joints comprising intricate mechanisms. This solution's complexity is a driver for mass and costs. Thus, today the transportation aircraft as economical system will benefit more from simplification than from further increase of flight-physical performance.

Figure1: Efficient but complex high lift system of Airbus A320

About thirty years ago a new discipline of engineering called *smart structures* appeared. The fundamental principle is the direct integration of active elements into the lightweight structure. Together with sensors and control units active systems can be realised able to autonomously adapt to mission and environmental requirements. In terms of the adaptive wing this approach is fascinating since distributed actuation based on multifunctional materials like piezo ceramics (PZT) or shape memory alloys (SMA) promises solutions of low complexity and of low mass. Encouraged by considerable successes of smart structures in dynamic applications euphoric statements regarding achievable benefits for commercial aircrafts were made. But until today large scale morphing has not yet been realised compatible to low mass and low energy requirements. Thus, the focus of research in smart aircraft structures was moved away form flight physical benefits and shifted to new - in majority military - aspects like multi mission and stealth capacities.

The authority of an actor over a passive structure is defined by the prevailing stiffness ration. Hence, state-of-the-art aircraft structures, which are designed for maximum strength and stiffness, are by nature badly conditioned to be activated. Since a couple of years structures with selective high elasticity for efficient activation are under developments which in the same time cope with strength and stiffness requirements. So called *compliant mechanisms* usually employ substructures based on struts in more or less complex arrangements. The fundamental approach is often similar to classic wing adaption mechanisms. But the realization considers modern light weight concepts like the substitution of pin hinges by solid state solutions and improves the structures' properties for activation significantly. Figure 2 shows the Belt Rib Concept developed at DLR. The combination of belt and struts results in a rib structure which provides high elasticity for one specific deflection mode desired and is stiff for all other deflections [1].

Figure 2: Belt Rib Concept

Anyway; strut constructions shift the load paths from the surface to the substructure going in line with reduced exploitation of moments of inertia and implying multiple discrete load introductions. This mass driver can be reduced by distributed substructures based on combs or anisotropic foams. To be highlighted in this context is the *Selective Deformable Structures* concept (SDS) which was developed within the European FP 5 project 3AS [3].

2 Smart Tailoring

Fibre reinforced composites offer a great potential in light weight design, if the fibres' mechanical properties can be exploited in the structure to its best. Although there are elementary concerns about the state-of-the-art in composite sizing, fundamental design principles can be formulated. Key factor is the tailoring of material for loads, which comprises both the fibre angles in the plies and the stacking sequence of plies. Best results will be obtained if the canalisation of loads into the shells is continued inside the material; hence load paths are conform to fibre paths resulting in minimum shear loads for the matrix. In difference to isotropic materials for composites 3D considerations even in shell like structures are mandatory [5]. Besides all theory, manufacturing constitutes an own challenge [2]. Techniques like *tailored fibre placement* or *tape draping* enable complex layouts but are of disadvantage concerning processing time and still limit the design space. Anyway, future high performance structures will be optimised for loads.

Consequent anisotropic lightweight design saves mass by elimination of not strength relevant fibres out of the composite. In the same time stiffness in this direction is reduced. Hence mass reduction goes in line with increased elasticity, which is the necessary and today lacking property for efficient activation.

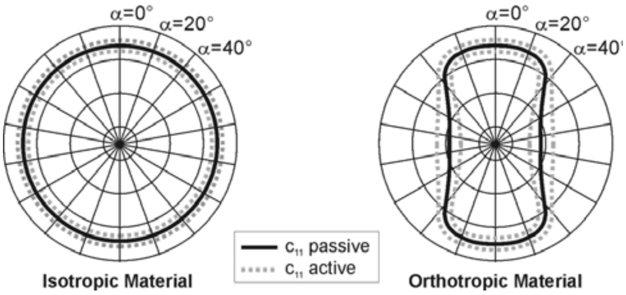

Figure 3: Activation of anisotropic material

The synergetic combination of *smart structures* and *structural tailoring* is following designated *smart tailoring*. The approach does not require modifications of the general structural design and is capable to exploit moments of inertia available. Smart tailoring primary aims at the skins. To some extend substructures can be tackled in the same way or use compliant mechanisms. The magnitude of achievable deflections is limited by the maximum strain of the matrix material. In well designed anisotropic composites loads will increasingly be shifted into the fibres permitting to introduce novel matrix systems of higher elasticity. Smart tailoring is expected to provide morphing of medium magnitude at strict compatibility to requirements of mass and complexity which are the main targets in transportation aircraft design today.

The directions in favour for actuation result from light weight design. Thus; active shape adaption can be realised efficiently for deflection modes which are not linear combinations of sizing loads' deflections. In other words: If the sizing loads lead to pure up bend of the wing, anisotropic design will precisely restrict this up bending deflection. Active camber may be introduced efficiently while active bending is constricted by the passive structure. This interrelationship is incompatible to the common smart structures approach of direct elimination of undesired deflections. Hence smart tailoring will usually not provide predefined deflections but it can provide desired change in aerodynamic pressure distribution using a priori unknown active shape modifications. Anyway, the intention is usually not, to mimic conventional control surfaces, but to attain aerodynamic effects. This approach strictly requires interdisciplinary design.

For an aeroelastic wing, shape adaption means to shift from one state of aeroelastic equilibrium to another. Thus; active morphing is always superposed by the subsequent aeroelastic deflections which can easily be in the same magnitude of the active engagement. Considering these effects is a mandatory challenge especially in the transsonic regime and in high lift configurations, where air flow is complex and sensible in the same time [4].

To some extend flying shapes can be influenced by passive aeroelastic tailoring. This technique uses structural coupling effects, which are installed by rotating the usually orthotropic material out of the main load path. A wide variation of twist and bend is permitted but a reduced exploitation of the material's strength potential is implied [4]. In terms of multiple load case design anisotropic materials always include structural couplings. Hence, smart tailoring has to comprise aeroelastic tailoring strategies. Deviation from the initially light weight optimised design might provide desired deflections at less effort than active shape control; but at a lower level of versatility. In hybrid approaches rotation of fibres can additionally be used to adjust elastic directions and to adapt active deformations to aerodynamic needs.

Hence; at each location of the structure active composite design has to make the trade between directed strength and elasticity, elastic couplings and proportion of integrated active material. The system's performance is to be evaluated for multiple strength and performance relevant load cases in terms of resulting mass and aerodynamic efficiency. For all this, aeroelastic interactions and high fidelity aerodynamics play dominant role and therefore have to be considered [4].

The DLR currently develops and investigates a numerical optimisation process for aircraft structures following the Smart Tailoring approach which able to cope with interdisciplinary high fidelity requirements. The following chapters present extracts from the ongoing work aiming at smart winglets of 'megaliner' configurations. The active shape adaption can be used for load reduction, performance driven control of airflow, low noise drag creation without lift decrease and for destabilisation of wake vortex. The addressed benefit of smart structures compared with a trailing edge tab is reduced mass and complexity.

3 Simulation

Both disciplines aerodynamics and structures require high fidelity tools to resolve the addressed effects. A simulation framework was established comprising Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA). Stationary interactions are considered using a weak coupling algorithm.

Aerodynamic calculations are performed to assess performance and to obtain precise loads which are obligatory for stress driven structural sizing. In cruise flight of modern transportation aircrafts transsonic effects play dominant role. The state-of-the-art in analysing these effects constitutes aerodynamic codes solving the compressible three dimensional Raynolds Averaged Navier Stoke equation (RANS). In the presented work the DLR code FLOWer for structured grids is used with wing-body models of 1.5M-2.5M cells. Turbulence is considered using the Baldwin-Lomax model. More detailed models up to multi body high lift configurations can be used in the framework employing the DLR RANS solver for unstructured grids TAU.

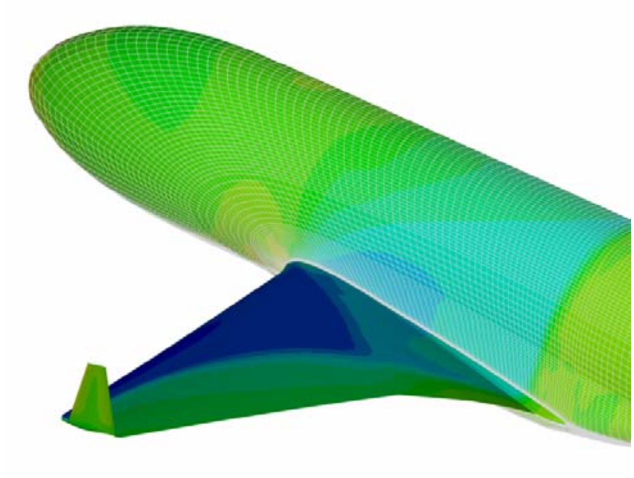

Figure 4: Undeformed CFD model, local c_P at high c_L in cruise flight condition

Structural Models of the wing are obtained using the DLR wing generation tool PARA_MAM [7]. Based on a full parametric description of the inner structure and the aerodynamic surface mesh as contour reference all geometric keypoins are calculated and subsequently output as complete input deck for the FEA pre-processor. In this work the commercial FEA code ANSYS is used due to the included scripting capacities. The structure shows a realistic rib-spar design and is idealised using SHELL 99 elements which provide up to 250 layers. Through-the-thickness information is calculated based on the classical lamination theory (CLT); implying simplifications of 3D stress/strain states [5]. Stringers are considered implicitly by stiffness equivalent layers in the wingbox shells. The wing sections outside the wingbox contain movable high lift devices, which conventionally are considered to not influence the global wing elasticity. Therefore the skin in these areas is reduced in stiffness by three orders of magnitude; contrariwise to the ribs. Since nodes between the ribs in the elastic regions are prohibited mesh at the wingbox interfaces was partially not continuous in fine models. In the study model size ranges from 50k to 250k degrees of freedom (dof). The structural problem is considered to be reversible and linear.

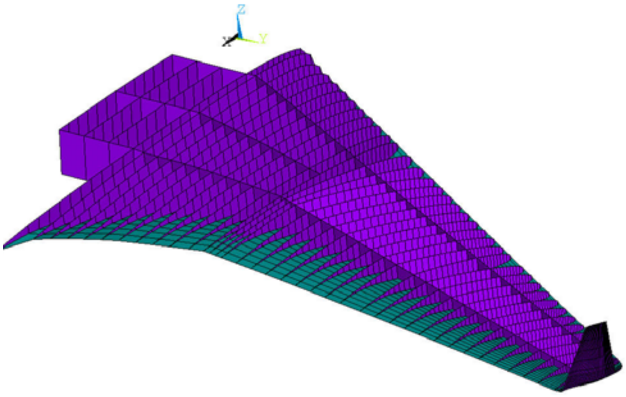

Figure 5: FEA model

Coupling is established using a sequential algorithm: Pressure is mapped from the CFD solution to the nodes of the FEA grid. The following FEA analysis delivers surface deflection to be mapped back to the CFD mesh, which subsequently is deformed and resolved. This approach permits to use the high sophisticated codes in both disciplines and enables high fidelity simulations. The process is automated for distributed computing inclusive interfaces for high performance computers like NEC SX6 and uses transparent ascii data exchange. On average office PCs (P4, 3GHz, 2GB RAM) states of equilibrium can be computed for presented models within approximately 5 hours. The integrated cross-grid interpolation is realised based on volume splines [4].

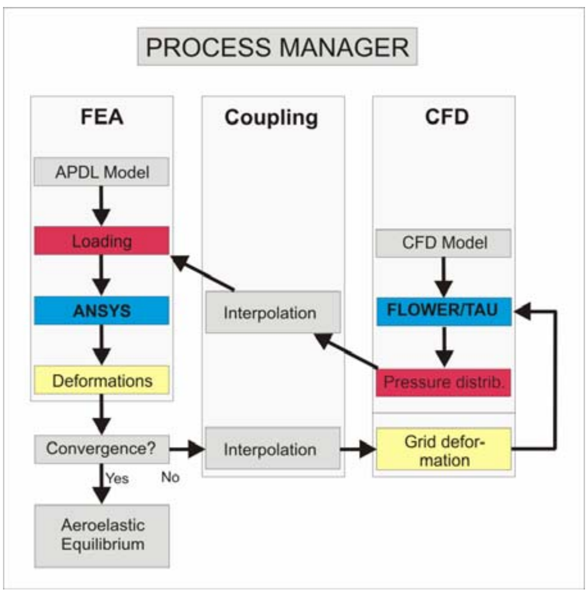

Figure 6: Sequential coupling algorithm

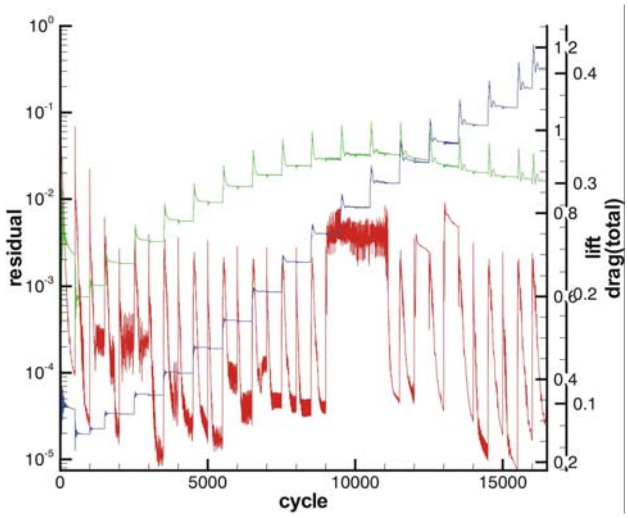

Figure 7: Residual, lift and drag coefficients of aeroelastic coupled alpha variation

4 Sizing Infrastructure

The introduced simulation environment is appropriate to calculate high fidelity aerodynamic performance and structural stress for realistic wing models. Structural optimisation in terms of smart tailoring has to determine for each element's layer the best thickness, orientation angle and material. For simplification uniform unidirectional CFRP material type is assumed. Only the directed thermal expansion coefficients are kept variable to introduce active materials via the thermal analogon. Anyway, problems of typically 50k to more than 5M design variables can not be handled by mathematical optimisation techniques directly.

Alternately, a stress based sizing infrastructure was created to limit the design space as far as possible using mechanically founded sizing rules. S_BOT (Sizing roBOT) is a suite of macros written in the ANSYS Parametric Design Language (APDL). ANSYS macros are of ascii format and therefore can be executed using classic ANSYS on any ANSYS supported hardware platform and operating system. S_BOT is an infrastructure to automatically analyse multiple load cases. A text input file serves as batch run friendly user interface for all specifications such as material limits, loadcase descriptions and sizing strategy. The initial FE model for sizing has to consist of S_BOT supported shell elements and is designated in the input file via its filename. PARA_MAM is not mandatory for model generation but advantageous since various synchronised conventions ensure correct and fast transfer of the high parametric models. Anyway, in the initialisation S_BOT modifies model properties compatible to its conventions. Loads are kept constant during the sizing process and may comprise surface load distributions from the aeroelastic process chain, which is located at super ordinate position embedding S_BOT.

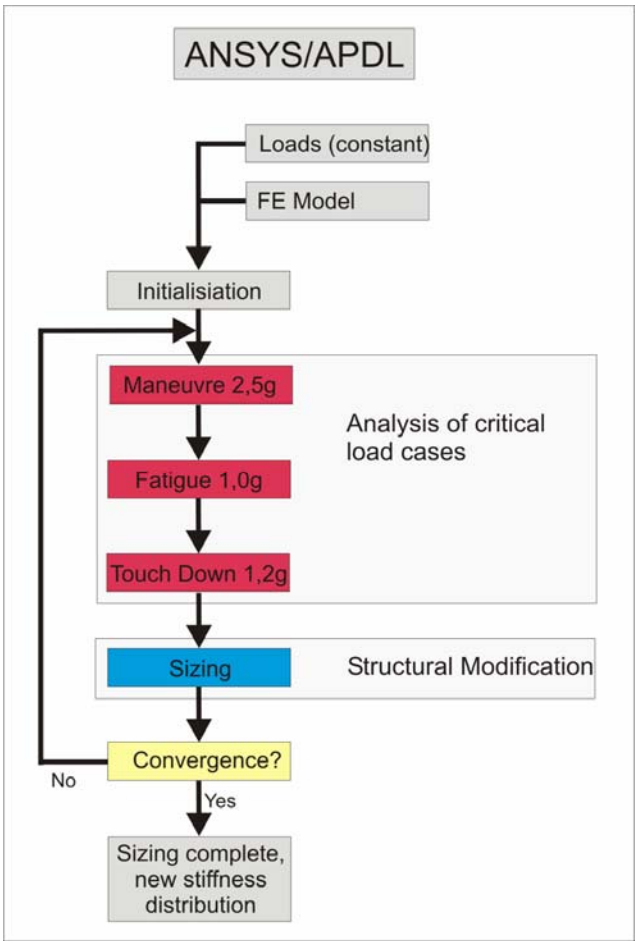

Figure 8: General S_BOT procedure; presented with the three typical loadcases

The post processing results at elements' centres are stored in four dimensional arrays with the number of element, layer and load case constituting the first three dimensions. The fourths dimension represents the results' age in the iterative design cycle, where a value of 1 designates the results from the current analyses, 2 the results from the last design cycle and so on. The availability of old results permits element- and layer-wise convergence monitoring, enabling numeric oscillation detection and adaptive adjustment of sizing parameters for process stability and speed. The depth of the results history can be adjusted in the S_BOT input file for memory saving.

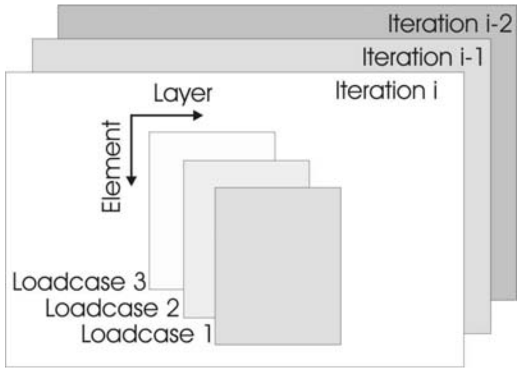

Figure 9: Data Structure of Analysis Results

Element properties are stored in arrays equally to the post processing data. After analyses a block of sizing routines modifies the element properties following predefined sizing rules, which can consider post processing items, model geometry properties and additional boundary conditions which all have to be provided in array format. After execution of the ultimate sizing macro ANSYS model matrices are updated to the new properties. Sizing rules contain pure vector and matrix operations enabling fast processing even of large models. The use of APDL as ANSYS internal programming language permits data handling inside the FEA code in binary format avoiding error-prone or slow data exchange between different codes. Sizing blocks can modularly be plugged in and widely be combined. Convergence of the process is monitored regarding the normalised rate-of-change for the layer properties, called thickness and angle residuals. The next chapters will provide details of sizing algorithms.

5 Direct Sizing Algorithms

Since light weight design is the origin of the smart tailoring concept this chapter introduces dedicated sizing strategies; the integration of extended design goals will be discussed in the next chapter. In the first step material is assumed to be isotropic reducing the design space to each element's thickness as design variables. For each loadcase component and equivalent stresses are compared to specified material limits, which may by different among the elements and loadcases e.g. ultimate and fatigue limits for different materials in the model. Gradient based deteministic optimisation for each individual element can be performed easily utilising the rule of proportion. For each loadcase a best thickness can be determined, whereof the maximum thickness among the loadcases has to be used for the model update resulting in *fully stressed design*. Process stability is ensured by relaxation factors which are adapted to residual behaviour. Figure 10 shows the mass and tip deflections evolution of a sizing for the 2,5g pull up manoeuvre starting from uniform thickness distribution. Figure 11 and 12 present skin thickness distribution at iteration 2 and 30 of the upper surface as element table in the ANSYS post processor.

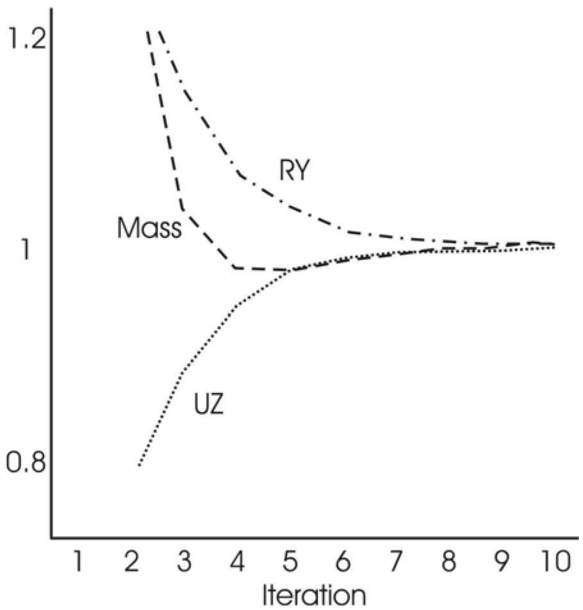

Figure 10: Mass and tip deflections convergence

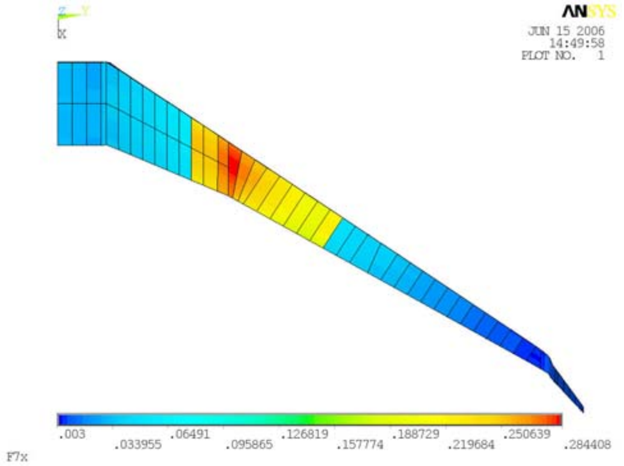

Figure 11: Wingbox thickness distribution after 2 iterations; element-wise sizing

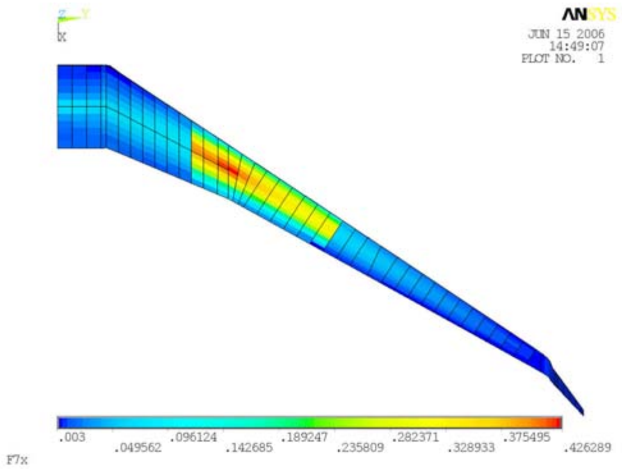

Figure 12: Wingbox thickness distribution after 30 iterations; element-wise sizing

The thickness residual declines continuously indicating convergent behaviour. Mass seems to converge within the first iterations but a small but constant increase remains. The thickness distribution shows maximum values at locations of maximum wing thickness. Hence material is arranged for best contribution to moments of inertia. Depending on post processing data used, the algorithm may keep on shifting material to maximum thickness locations resulting in a 'structure drop' in the wing. The cross section's shape evolutes to a shape which does not exploit moments of inertia what explains the remaining increase of mass after the lightest solution.

Besides more elaborated sizing rules results can be improved by specific restriction of thickness distribution. For this aim optimisation regions can be specified which consist of continuous element pattern designated as components in ANSYS. Parametric distribution functions represent the skin thickness over normalised optimisation region coordinates. Parameter fit leads to approximations of the element-wise calculated thickness distribution featuring characteristics defined by the type of function. Possible approaches are Taylor or Hermité polynomials as well as spline functions with variable control points. Individual element thickness is subsequently interpolated from the distribution function.

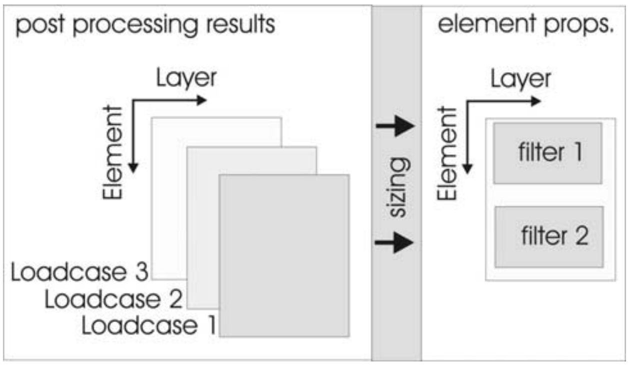

Figure 13: Sizing and filter arrangement, data structure

This filter also introduces boundary conditions of manufacturability what is of special interest for smoothing scattered results from multiple loadcase design. Further on elastic properties of the wing can directly be influenced by additional weighting. Distribution functions may be used for all design variables delivering an element independent description of the model properties. This enables to map the properties to models of equal optimisation regions but different discretisations enabling variable fidelity optimisation. Multiple filters like distribution function plus additional thickness stepping can be combined, but may have disadvantageous effects on numeric stability.

Anisotropic material offers the material orientation as additional design variable. The simple most set up is two layer shell elements with one isotropic and one orthotropic layer representing the skin and a stiffness equivalent representative of the stringers. Regarding light weight aspects the best performance can be achieved if the local axes of orthotropy are aligned with local load path directions [6]. S_BOT calculates principal stresses for sizing and supports also the layer wise angle for sizing routines. Experiences confirm a strong influence of material orientation on stress distribution what may lead to an instable sizing process. Modifications have to be made charily limiting the maximum angle change to approximately 5 degree per iteration. Further on best convergence behaviour was achieved if thickness and orientation were not modified in the same iteration loop.

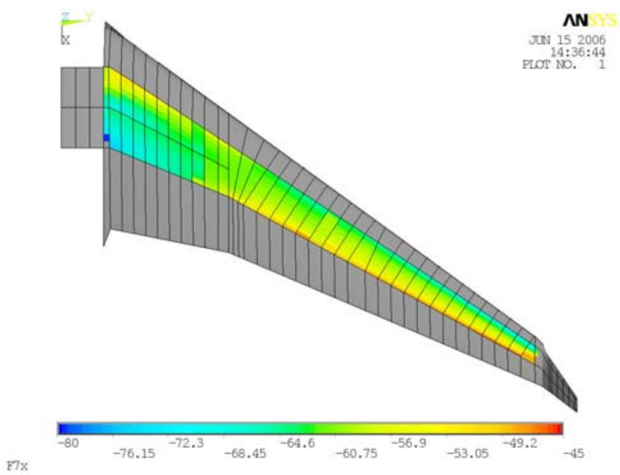

Figure 14: Angle distribution skin up

Fibre reinforced composites usually consist of multiple layers with anisotropic elasticity and strength. Sizing has to consider different failure modes like fibre and matrix fracture. The enormous and increasing number of widely conflicting failure criterions indicates the problem with the comprehension of fundamental mechanics of composites. For S_BOT the Puck criterion was selected since it is reasonable and widely accepted. Layer wise sizing is implemented; even though the combined assumptions of shell theory, classical lamination theory and the Puck criterion only permit sizing at elaborated pre-design level; especially if layers of active material are included [5].

Although the criterion requires a more complex sizing algorithm, the implementation does not cause problems for the iterative process. But extended filter functions are necessary e.g. to ensure symmetric laminates and continuous fibre paths in every layer. Currently further restrictions are used to obtain better understanding of the sizing process and of best solutions. Examples are rotation of only one layer or rotation of the whole laminate. Layer thickness fractions are kept constant or are only varied for single layers.

6 Optimisation Based Design Algorithms

In multiple loadcase design of anisotropic structures it is difficult to analytically determine the best element properties. Is the orthotropic material to be aligned with the maximum stress direction, with the averaged or the balanced stress? Especially in complex structures interactions between the elements make a numeric approach necessary. Anyway, analysis results provide characteristic properties like the three stress values mentioned permitting to make a good guess for the best solution and to limit the design space to few reasonable solutions. The parameters of mechanical sizing functions constitute the unknowns for mathematical optimisation. Boundary conditions of manufacturability demand the organisation of these variables using distribution functions. Hence, design space could be restricted by permitting mechanically reasonable and producible solutions only. S_BOT is called from super ordinate optimisation routine which searches for the best distribution function parameters. Besides mass other targets like bend and twist distribution can be used in this optimisation taking classical goals of aeroelastic tailoring into account.

Sizing for light weight design uses principle stresses of strength relevant loadcases as characteristic references. Creating new loadcases which apply the desired deflections of smart structured to the model delivers orientations of desired high elasticity. The sizing routines use a weighting factor to make the trade between strength and elasticity targets.

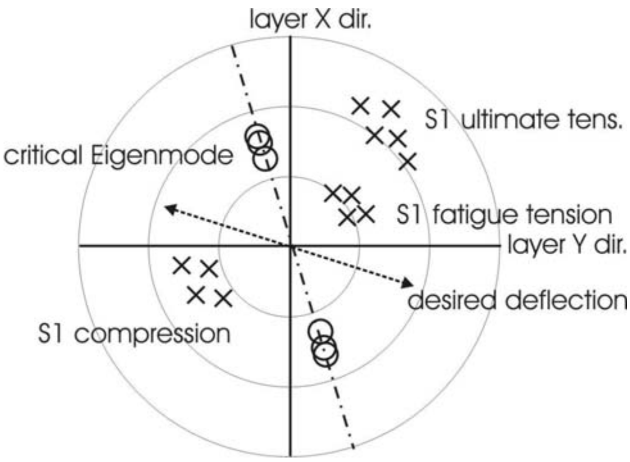

Figure 15: Characteristic requirement plot

The automated placement of actors is not yet realised, although active materials are well suited to be integrated via the thermal analogon using sizing routines. Maximum strain and strain energy are meaningful characteristics for the algorithms.

Eigenfrequencies are important for dynamic aeroelasticity and can additionally be integrated into the structural design process. Performing modal analyses after each iteration loop delivers strain directions of the modes. If the frequencies of critical modes are too low, the elements of maximum strain in this mode consider the strain direction in sizing equal to stresses with strength requirements, whereas the virtual stress level is iteratively increased until the frequency has reached the target. This approach promises selective adjustment of critical Eigenfrequencies at minimum mass penalty.

7 Conclusion and Outlook

Morphing wings require selective elasticity for efficient activation. It is aspired to maintain the concept of shell based light weight structures for mass and complexity reasons. Thus, selective elasticity has to be provided by the material instead of intricate mechanisms. Smart Tailoring is a dedicated design concept combining Smart Structures and Structural Tailoring in a synergetic manner. A numeric design process was introduced capable to integrate multiple targets into structural design. The contained simulation framework comprises coupled high fidelity CFD and FEA methods which are necessary to resolve the relevant effects of transsonic aerodynamics and composite structures. Mechanical analysis considers each element's individual layer. The design space is restricted by distribution functions of element properties which introduce boundary conditions of manufacturability. The determination of best laminate property distribution uses hybrid algorithms based on mechanically driven sizing rules and super ordinate mathematical optimisation of mechanic sizing parameters.

The sizing framework is operable at DLR and is currently used to investigate sizing and optimisation strategies for active and passive structures. Active winglets for a megaliner configuration serve as initial testcase to assess differences in structural mass and active deflections compared with winglets equipped with trailing edge tabs. A high potential is seen in the replacement of conventional droop nose devices by active elastic structures, where Smart Tailoring hast the potential to make a significant contribution.

8 Acknowledgement

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