Multifunctional Skin Material for Morphing Leading Edge Applications

Markus Kintscher, Hans Peter Monner, Srinivas Vasista, Anton Rudenko

AFOSR Workshop on "Active Composites for Morphing Structures"

Copenhagen, Denmark
Overview

- Motivation & Challenges for morphing leading edge
  - Laminarity
  - Large scale morphing
  - 3D morphing
  - „The real world“
- Approaches for kinematics and compliant mechanisms
  - Kinematics design
  - Flexural joints
  - Compliant mechanisms design
- Approaches for skin design
  - GFRP 3D
  - GFRP-EPDM
  - GFRP with integrated layers
  - Polyurethan with foam
Motivation & Challenges for morphing leading edge

Laminarity

• High-Lift devices on leading and trailing edge for lift generation at low speed (take-off & landing)

• Common high-lift devices (Slat, Krueger) are highly effective ($c_{a,\text{max}}$) but exhibit slots, gaps and steps

→ Transition to turbulent flow on main wing due to steps and gaps

→ Drag due to steps and gaps

→ Primary source of airframe noise in approach/landing
Motivation & Challenges for morphing leading edge
History of Smart Droop Nose Development at the DLR

- **SmartLED**
  - 2007-2010
  - **Ground Demonstrator, 3D, Feasibility**

- **SADE**
  - 2008-2012
  - **Wind Tunnel Model, 2D, Shape Control**

- **JTI-SFWA**
  - 2009-2013
  - **Ground Demonstrator, 2D, Kinematics, Fatigue**

- **SARISTU**
  - 2011-2015
  - **Wind Tunnel Model, 3D, Integration of Functionalities & Shape Control & Kinematics**
Motivation & Challenges for morphing leading edge

Large Scale Morphing

- SFB880: national special research program for the development of upstream High Lift technologies
  - Range: 2000km
  - Capacity: 100 Pax
  - STOL capability (800m)
  - Reduced level of the ground noise

- Part A: Aero-acoustics
- Part B: **Efficient High-Lift**
  - Reduction of power consumption of Coanda-flap high-lift system
- Part C: Flightdynamics
Motivation & Challenges for morphing leading edge

Large scale morphing

- Morphing leading edge for an active blown High-Lift system of a regional airliner
  - Gaps: noise and drag → Gapless active high lift system
  - Coanda effect is used for significantly increasing lift generation

Cruise position

High-Lift position

noise sources
Motivation & Challenges for morphing leading edge

3D morphing

- Droop-nose morphing of a regional jet-liner wing-tip
  - Highly 3D
    - 35° sweep
    - Taper: chord and thickness
    - Dihedral
    - Double curvature
    - Streamwise morphing target shapes
  - Developing optimization tools to account for these geometries
Motivation & Challenges for morphing leading edge

3D morphing

- Small morphing deflection: 2°
  - Aeroelastic benefits, e.g. prevention of aileron efficiency loss with increasing dynamic pressure

- Drag reduction
Motivation & Challenges for morphing leading edge
„The real world“

- Challenges for morphing devices
  - Large scale deformation
  - Integration of additional required functionalities
  - Concepts for integration and repair/maintenance

- Large Scale
  - Aeodynamic optimization of leading edge profile with max curvature difference \( \pm 20\text{m}^{-1} \)
Motivation & Challenges for morphing leading edge

„The real world“

- Challenges for morphing devices
  - Robustness at large scale deformation in combination with environmental conditions in operation:
    - Temperature (-50°C – +90°C)
    - Sand/Rain Erosion
    - Corrosion (skydrol, marine water, …)
- Example: Development of a morphing fin trailing edge with SKF, Blohm + Voss and partners for real life operational conditions

Overview

• Motivation & Challenges for morphing leading edge
  • Laminarity
  • Large scale morphing
  • 3D morphing
  • „The real world“

• Approaches for kinematics and compliant mechanisms
  • Kinematics design
  • Flexural joints
  • Compliant mechanisms design

• Approaches for skin design
  • GFRP 3D
  • GFRP-EPDM
  • GFRP with integrated layers
  • Polyurethan with foam
Aproaches for kinematics and compliant mechanisms

Kinematics design

- Given **Target Shape**
  - Aerodynamic or Hydrodynamic optimization
- Structural Design
  - **Interface Points**
    (Structure ←→ Mechanism)
- Design of Kinematics with **Trajectories**
  - Guidance Mechanism for the morphing structure during movement
  - Load transfer of aerodynamic/hydrodynamic loads
Approaches for kinematics and compliant mechanisms

**Kinematics design**

- Pre-Design of Skin and Kinematics (2D)
- Detailed Design (3D)

- Aerod. Target Shape
- Initial Skin Design
- 2D parametric FE, Optimal Support Pos.
- Kinematical Path, Strains, Deformations, Stresses
- 3D FE model
- Optimization of the Design of Omega-Stringers wrt. stability and strength requirements
- Optimization of layer stacking sequence/ laminate layup wrt. target shape, stability and strength requirements
- Feedback data for other disciplines
Aproaches for kinematics and compliant mechanisms

Kinematics design

- **Design parameters** of the skin optimization:
  - Stiffness of skin segments along the skin perimeter
    - Thickness or layup variation, …
  - Positions of the interfaces to the compliant kinematic system
  - Modulus and the direction of the actuator load vectors on these interfaces

*CAD-construction of the morphing leading edge*
Aproaches for kinematics and compliant mechanisms
Skin & Kinematics design (large scale morphing)
Aproaches for kinematics and compliant mechanisms

**Flexural Joints for Compliant Mechanisms**

- Substitution of the state of the art kinematics by flexural joints and compliant mechanisms

- Numeric and experimental parametric studies on GFRP-Polymer joints under multiaxial loading
Aproaches for kinematics and compliant mechanisms
Compliant mechanisms design

Advantages of Compliant Mechanisms
• lightweight structures
• reduced assembly complexity
• no backlash

Topology Optimization
• find best structural layout starting from a “blank canvas”
• continuum gradient based via SIMP, sensitivity analysis and MMA
• 2D plane stress
• linear FEA routine (small target deflections)
• Shape control formulation: precision displacement
• Stiffness functions: load capability
Aproaches for kinematics and compliant mechanisms

Compliant mechanisms design

- Topology post-processed
- Superelastic nickel titanium (>2% strain)
- Manufactured by wire electrical discharge machining (EDM, 5 mm plate form)
Overview

• Motivation & Challenges for morphing leading edge
  • Laminarity
  • Large scale morphing
  • 3D morphing
  • „The real world“
• Approaches for kinematics and compliant mechanisms
  • Kinematics design
  • Flexural joints
  • Compliant mechanisms design
• Approaches for skin design
  • GFRP 3D
  • GFRP-EPDM
  • GFRP with integrated layers
  • Polyurethan with foam
Approaches for skin design

**GFRP 3D**

- tailored stiffness:
  - optimized skin thickness distribution
- thickness achieved via appropriate ply stacking
- GFRP Hexcel HexPly® 913 prepreg plies
- skin – compliant substructure interface: stringer
  - i.e. load introduction point
- 2D concept of SADE program →
  - Re-developed in a 3D environment in NOVEMOR
- Simplex algorithm
- automated and iterative
- objective function: LSE clean and droop configurations
  - multiple FEA solutions via Ansys:
    - combined shape change and stiffness functionality

**DVs 1 – 16:**
- skin thickness at 21 points
- [1 – 4] mm
- bilinear interpolation

**DVs 17 – 18:**
- stringer position at stations 2 and 4
- [35 – 55] % station perimeter length
- spline interp. and extrap.

**DVs 19 – 20:**
- force magnitude at CM stations
- [50 - 650] N
Approaches for skin design

GFRP 3D

3DSkinOpt post-processing
- algorithm established for ordered edge detection
- LSE 3D spline-fit based on coordinate parameterization for smooth contour generation
- export files to CAD
- 32 plies (HexPly® 913) as per stacking sequence
Approaches for skin design

GFRP 3D

Wind tunnel tests, Feb. 2015
- Univ. of Bristol, 7’ x 5’
  Low speed
- Assessment of structure (skin and compliant mechanisms) under aerodynamic loads
Approaches for skin design

**GFRP-EPDM**

- Hybrid skin design for high anisotropic skins

- High-Strain capability through combination of GFRP/EPDM-rubber (synthetic rubber)

- Combination of GFRP laminate with C/GFRP stiffeners in a rubber matrix

- Flexibility in chord direction – stiffness in span direction

Source: Andre Schmitz, IFL, TU-Braunschweig
Approaches for skin design

**GFRP-EPDM**

- A representative FE-element of a hybrid skin under bending load
  - Parametric boundary conditions
  - Reduced order modeling for large scale applications
- Experimental validation of the FE models
- Strength and fatigue investigations

**Source:** Andre Schmitz, IFL, TU-Braunschweig
Approaches for skin design

GFRP-EPDM

- Experimental and numerical investigations on the skin-kinematic interfaces
- Integration of dense meshed solid models in the optimization routines

A specimen with 30 micro strain gages in curved surfaces for the model validation

Investigation of strength of load application points under representative loading conditions (curved)
Approaches for skin design

**GFRP-EPDM**

- Strength of the interface under realistic loads

**Force – Displacement Curve of loading under 20° force application**

**Test of a double-L interface with a force under 20° load application**
Approaches for skin design

GFRP with integrated layers

- Integration of additional functionalities into a ‘baseline’ GFRP skin concept
  - Ice Protection System (IPS)
  - Lightning Strike Protection (LSP)
  - Erosion & Impact Protection
  - Bird Strike Protection
  - Improved Fatigue Behaviour
Approaches for skin design

GFRP with integrated layers

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Rib Station</th>
<th>Length</th>
<th>Test/Demonstrator</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>GT</td>
<td>Rib 10 – Rib 16</td>
<td>3656mm</td>
<td>Large scale test: wing bending, cyclic, heater-mat</td>
<td>Shape, Strain, Strength</td>
</tr>
<tr>
<td>WTT</td>
<td>Rib 13 – Rib 16</td>
<td>1760mm</td>
<td>Test under aerodynamic loads</td>
<td>Shape, Strain</td>
</tr>
<tr>
<td>BST</td>
<td>Rib 11 – Rib 12</td>
<td>1600mm</td>
<td>Bird Strike Tests, 3 configs: 2x splitter, 1 hybrid</td>
<td>Bird Strike Performance</td>
</tr>
<tr>
<td>Ti1</td>
<td>Rib 10</td>
<td>300mm</td>
<td>Demonstrator with Ti-foil (full-chord) &amp; heater-mat</td>
<td>Shape</td>
</tr>
<tr>
<td>Ti2</td>
<td>Rib 11</td>
<td>300mm</td>
<td>Small scale test with Ti-Foil (Patch)</td>
<td>Shape, Strain, Strength</td>
</tr>
</tbody>
</table>
Approaches for skin design
GFRP with integrated layers

→ Basic Design Specifications
→ (Pre-) Design based on target shapes

- Parametric Description of aerodynamic profile
- Aerodynamic Optimization (High-Lift, Cruise(VC))
- Assessment of Structural (Geometric) Boundary Conditions

Parameterization of the profile for CST method (class/shape function transformation)

Approaches for skin design
GFRP with integrated layers

→ Basic Design Specifications
→ (Pre-) Design based on target shapes

- Parametric Description of aerodynamic profile
- Aerodynamic Optimization (High-Lift, Cruise(VC))
- Assessment of Structural (Geometric) Boundary Conditions

Parameterization of the profile for CST method (class/shape function transformation)


- Minimum skin thickness
- Definition of a limit of difference in curvature

\[ \Delta \kappa_{\max} = 20 \text{ } \text{1/m} \]
Approaches for skin design

GFRP with integrated layers

“Integrated Structure and System Concept Definition”

- **Overall wing leading edge sections**
  - Three leading edge sections
    - Two Outboard Sections
    - One Inboard Section
  - Kinematic Stations are consistent with given rib positions
- Integration of bird strike protection and kinematics
- Integration of additional functional layers
Approaches for skin design

GFRP with integrated layers

“Integrated Structure and System Concept Definition”

- Overall wing leading edge sections
  - Three leading edge sections
    - Two Outboard Sections
    - One Inboard Section
  - Kinematic Stations are consistent with given rib positions

- Integration of bird strike protection and kinematics

→ Design Space is limited!

- Integration concept of additional functional layers
Approaches for skin design
GFRP with integrated layers

→ Integration of bird strike protection and kinematics

• Shot on morphing leading edge with integrated bird splitter and separate hybrid splitter concept
Approaches for skin design
GFRP with integrated layers
Approaches for skin design
GFRP with integrated layers
Approaches for skin design

**GFRP with integrated layers**

“Integration of additional functionalities”

- Overall wing leading edge sections
- Integration concept of BSPS and kinematics
- **Integration concept of additional functional layers**
  - Surface Protection
  - De-/Anti- Icing
  - Impact Resistance
  - Lightning Strike Protection

Comparison of rain and solid particle erosion durability of different materials

<table>
<thead>
<tr>
<th>Rain erosion</th>
<th>Paint</th>
<th>Rubber</th>
<th>Hard coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>(20 - 3000 impacts, 225 m/s, 2 mm drop size)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Solid particle erosion</th>
<th>Metall</th>
<th>Paint</th>
</tr>
</thead>
<tbody>
<tr>
<td>(5 g silica sand 220 µm, 55 m/s, 2 g/mm)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Approaches for skin design

**GFRP with integrated layers**

"Integration of additional functionalities"

- Overall wing leading edge sections
- Integration concept of BSPS and kinematics

**Integration concept of additional functional layers**
- Surface Protection
- De-/Anti- Icing
- Impact Resistance
- Lightning Strike Protection

*Source: GKN*
Approaches for skin design
GFRP with integrated layers

“Integration of additional functionalities”

- Overall wing leading edge sections
- Integration concept of BSPS and kinematics
- Integration concept of additional functional layers
  - Surface Protection
  - De-/Anti-Icing
  - Impact Resistance
  - Lightning Strike Protection
Approaches for skin design
GFRP with integrated layers

“Integration of additional functionalities”

- Overall wing leading edge sections
- Integration concept of BSPS and kinematics
- Integration concept of additional functional layers
  - Surface Protection
  - De-/Anti-Icing
  - Impact Resistance
  - Lightning Strike Protection
Approaches for skin design

GFRP with integrated layers

- Limited Design Space at outboard: Integration brackets can be realized but lead to strain peaks (which limit the degree of morphing) and local stiffening in chord (which increases local changes in curvature when deployed, waviness)
- Metallic erosion protection shields make the tailoring to target shapes difficult due to their high stiffness and exhibit a poor fatigue behavior
- Max. Strain: Functional Layers to be integrated must be high strain capable and must be designed as thin as possible
- IPS: The dielectric properties of the basic material must be improved. It triggers additional thickness due to electr. isolation and for their part again higher heater-mat temperatures due to thermal isolation
- Lightning strike protection without application of metallic foils needs to be investigated
Approaches for skin design

Polyurethanan with foam

- Structural Concept for a Morphing (FIN) Trailing Edge

Fig.: Pre-Design Finite Element Analysis: Strain Distribution in Deployed Position

Fig.: Design Concept for Integrated Stiffeners and Material Combination
Approaches for skin design

Polyurethan with foam

- Development of a morphing trailing edge fin

- Material combination of
  - GFRP
  - Polyethylene Foam
  - Polyurethane Skin

- Coupon and Component Tests
  - Static material tests under environmental conditions i.e. temperature and marine water in combination
  - large scale cyclic component test

Fig.: Results of cyclic tests of the morphing trailing edge segment

Continuous increasing complexity and details in FEA Design combined with validation by experimental tests

- Variant 0: 2-dimensional, GFRP
- Variant 1: 2-dimensional, GFRP + PU-Foam
- Variant 2: 2-dimensional, GFRP + different foams
- Variant 3: 2-dimensional, GFRP + PE-Foam + PU-Skin
- Variant 4: 3-dimensional, GFRP + PE-Foam + PU-Skin

Approaches for skin design
Polyurethan with foam
Approaches for skin design

Polyurethan with foam

- Flexible Morphing Trailing Edge
- In-Service since 06/2014 on a marine vessel
Outlook – Main Challenges

- Concentration on conventional high-strain capable materials (GFRP, CRRP) for high acceptance in industrial applications → Structural Design/Good Ideas as enabler for industrial application

- Basic Research in terms of material combinations (GFRP/Elastomers, Compliant Mechanisms, Integration of Functionalities, Hydrophobic Surfaces)

- Manufacturing considerations (complex geometries, cost reduction, material wastage reduction) of these materials e.g. 3D printing of superelastic metals

- Concurrent optimization of skin and substructure kinematics as a whole, integrated system, including energy, weight and stress objectives and/or constraints