The Virtual Product
Next Generation Simulation for Future Aircraft Design

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Outline

- Introduction
- Virtual Product
- Simulation Scenarios
  - Performance
  - Flight Envelope
  - Design
- DLR’s Research Areas
- Concluding Remarks

Acknowledgement: Thanks to numerous DLR colleagues for providing material for this presentation
What is the Future?
What is the Future?

Today's products highly matured: Are improvements possible at all?

- Numerical simulation may be the key enabler
- Multidisciplinary optimization will be mandatory
- Future Designs via concept of “Virtual Aircraft”

- Concept of Virtual Product extends simulation to complete a/c lifecycle
Virtual Product in Aeronautics Components

**Digital Aircraft:** Encompasses design, testing, manufacturing & certification process

**Digital Twin:** Reflects the use of a particular series-production aircraft to predict the impact on its operational capability, maintenance & overhaul requirements

**Digital Thread:** Addresses complete data flow from early concept phase to final decommissioning, including feed back from the Digital Twin into upgrades of the current Digital Aircraft or improvements of future designs
The Virtual Product – DLR Guiding Concept in Aeronautics

Digital description of an aircraft with all its properties and components **based on highly accurate physical and mathematical models**
- Across all disciplines
- In every phase of the development phase
- Across entire aircraft lifecycle

Concept allows DLR research to scientifically track all phases of aircraft development including aircraft design & testing, manufacturing, certification, operations & impact on environment

→ **Virtual Overall System Capability**
Which Simulations are Required?

Aerodynamic performance predictions
- Cruise (L/D), high lift ($C_{l_{\text{max}}}$)
- Detailed data at special points of the envelope

Challenges
- Flow separation
- Laminar/turbulent transition
- Flexible aircraft

→ High-fidelity modelling
Multi-Disciplinary Aircraft Simulation

Trim of *elastic* transport aircraft, “One-Engine-Out Case”

- Horizontal *aeroelastic* trim of XRF1
- Ma = 0.85, Re = 60x10^6, m = 198t, h = 10.7km
Multi-Disciplinary Aircraft Simulation

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Aerodynamic performance predictions
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Aerodynamic loads predictions
- Critical forces and moments
- Data along the full border of the full envelope

Challenges
- Flow separation
- Unsteady effects
- Moving control surfaces
- Structural properties
- Multidisciplinary analysis
- Huge parameter space

⇒ High-fidelity simulations
Loads Predictions

Linear/Non-Linear Steady/Unsteady Flows

Computational Flight Testing

50 flight points
100 mass cases
10 a/c configurations
5 maneuvers
20 gust load cases
4 control laws

~ 20,000,000 simulations

All Configurations

Cruise, Clean

Spoiler

High-Lift

Goal: Virtual Aircraft Model based on High-Fidelity Simulations
Virtual Aircraft Model

Time-accurate multi-disciplinary manoeuvring aircraft simulation

“Fly the equations”

Generation of surrogate model of sampled static & dynamic aerodynamic data relying on high-fidelity tools

“Fly through the database”

M.D. Salas
Virtual Aircraft Model: “Fly the Equations”
Wake Vortex Encounter

- A320 flying through wake vortices of A340
- $Ma = 0.78$, $h = 37,000$ ft
- $m_{A320} = 70$ t
- $m_{A340} = 190$ t

- Perform unsteady coupled simulation (CFD-FM)

Aircraft is in the plain of the vortex pair
$\phi = 5^\circ$

initial situation

mid of simulation

100m

mid of simulation, slice through the disturbance velocity field

A320 is 5 m beneath vortex pair
Virtual Aircraft Model: “Fly the Equations”

Wake Vortex Encounter

A320 flying through wake vortices of A340
Virtual Aircraft Data Model
“Flying through the Data Base”

Huge sets of aerodynamic data required for complete flight envelope as input for

- Flight simulator data base
- Development of flight control system
- Layout of control surfaces
- Structural layout and sizing

Surrogate Models based on high-fidelity simulations
- Accurate & fast predictions
- Static / dynamic loads
- Forces/moments, derivatives
- Surface pressure, skin friction, ..
Aerodynamic Data for Loads
Reduced Order Modeling (ROM)

Goal
⇒ Provide quantitatively accurate descriptions of the aerodynamics with few degrees of freedom than the original CFD model

ROMs
⇒ Operate on parameterized generated data (snapshots)
  ⇒ scalar quantities: lift, drag and moment coefficients $C_L$, $C_D$, $C_M$
  ⇒ surface quantities: pressure and shear stress $c_p$, $c_f$
  ⇒ volume quantities: primitive variables $\rho$, $v_i$, $p$, $T$

![Diagram showing offline and online processes with different angles and snapshots](image)
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Loads Prediction* – Time Accurate Surrogate

*) \((1 - \cos)\)-gust
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→ Multi-Disciplinary Optimization
Gradient-Based High-Fidelity MDO Chain
Aero-Structural Optimization

**Wing design**

*Objective* = \( \frac{1}{C_W} \times \frac{C_L}{C_D} \), with \( C_W = \frac{\text{Current structural mass}}{\text{Reference mass}} \)

**Design parameter**
- **360** shape design variables
- **350** structural thickness variables

**Constraints**
- Lift & pitching moment coefficients
- Strength & buckling

**CFD/CSM-simulation per optimization step**
- Cruise point
- 7 critical load cases for structural sizing

Range increase ~ 4%

Airbus XRF1 configuration
DLR Research & Development Areas
Simulation Framework

- Tight coupling of all relevant aircraft disciplines (high-fidelity methods)
- Modeling of moving control surfaces
- Huge unsteady computations
- High performance computing
- Parallel multi-disciplinary environment
Full exploitation of future HPC systems
- Flexible building blocks
- Basis for innovative concepts & algorithms e.g. high-order-finite element discretization, adaptivity, ...
- Extension of application range
- Seamless integration into multidisciplinary simulation environment FlowSimulator
- State-of-the-art software engineering methods

- Separation of what is done locally (loop body) from how it is done globally
  - Implementation of the how logic just once in an HPC layer of the code framework (loop interface).
  - Only this has to be changed for porting to a new architecture.

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**DLR Research & Development Areas**

Next Generation Flow Solver *Flucs*

- **Framework**
  - HPC Layer
    - Network Communication (GASPI, MPI)
    - Shared Memory / Threading
    - SIMD
    - Domain Decomposition
    - Sorting
    - Sub-partitioning (threads)
    - Optimized memory access
  - Loop Interface
    - Element Loop
    - Face Loop
  - Solver Module
    - Gradient Computation
    - Flux Integration
    - Iterative Update
    - ...

- **Mesh**
  - discrete geometry
  - integration points

- **Recon.**
  - evaluate conservative variables
  - gradient-based reconstruction
  - polynomial evaluation

- **Closure**
  - additional variables (Gas model)
  - pressure, viscosity, ...

- **PDE**
  - evaluate fluxes
  - convection, diffusion
  - evaluate source terms

- **Upwind.**
  - add directivity of convection
  - depends on PDE and equation of state (Closure)

- **Disc.**
  - combine information to compute residual
Turbulence and Transition

- Accurate prediction of laminar and turbulent flows → Transition

- Dedicated turbulence model improvement → accurate prediction of flow separation

- Specific turbulence models and simulation concepts → resolution of detailed turbulence structure
Multi-level procedure

- Low-fidelity methods for overall aircraft design
- Fast methods for identification/computation of critical load cases
- High-fidelity methods for aerodynamics and structure
- Consistent stream from preliminary to detailed design
- Parallel software platform
- Workflow management
- Sequential multi-level MDF approach
  - Easier to deal with complexity
  - Easier to implement
  - Close to industrial processes
Virtual Product in Aeronautics
Potential and Requirements

Virtual design, testing and certification of future aircraft taking into account operational as well as environmental aspects

- Generation of all data necessary for certification / acceptance for complete flight envelope
- Combine / consolidate simulation data with experimental data (flight tests / windtunnel tests) as well as those of previous aircraft-design processes
- Identification and extraction of principles and rules relevant to design and certification / approval processes
- Deduction of concepts for future aircraft design process
- Data access and extraction, information management, knowledge generation
Virtual Product in Aeronautics Research Perspective at DLR

Dedicated new institutes

Existing Institutes

Inst. of Aerodynamics & Flow Technology
Inst. of Aeroelasticity
Institute of Materials Research
Institute of Structures and Design
Institute of Propulsion Technology
Institute of Combustion Technology
Institute of Flight Systems
Institute of Flight Guidance
Inst. of Air Transport and Airport Research
Inst. of Technical Physics
Air Transportation Systems
Flight Experiments

New Institutes

Software and Hardware
Institute of Software Methods for Product Virtualization
Dresden

Airframe Institute of Simulation & Test of Gas Turbines
Virtual Product House Augsburg
Bremen

Engine Institute for System Architecture
System Architecture Institute for System
Archtecture Hamburg

MOR Institute for Maintenance & Overhaul
Hamburg

Vehicle Operations
Virtual Product in Aeronautics
Improvement of Aircraft Performance

Digital Aircraft MDO & MDA
- Trade-off between disciplines

- cruise: Design for Performance
- Operation: Safety margins to boundaries of flight envelope

Flight envelope boundaries

F. Thomas, 1966

\[ \alpha \]

\[ M_{\infty} \]

subsonic transonic supersonic

Breguet-Formula
- SFC: Specific Fuel Consumption ➞ Engines
- W: Weight ➞ Structures
- L/D: Aerodynamic Efficiency ➞ Aerodynamics
- \( M_{\infty} \): Cruise Mach number ➞ Aerodynamics/Propulsion
Virtual Product in Aeronautics
Improvement of Aircraft Performance

Digital Aircraft MDO & MDA
- Trade-off between disciplines
- Assessment of operational limits

- cruise: Design for Performance
- Operation: Safety margins to boundaries of flight envelope
- Perspective: Reduction of margins

\[ \text{Cruise Altitude} \]

\[ \text{Trip Fuel} \]

\[ \text{Distance} \]

\[ \frac{\text{SFC}}{\text{M}_{\infty}} \times \frac{\text{W}}{\text{L/D}} \]

\[ \alpha \]

\[ \text{cruise flight} \]

\[ \text{subsonic} \quad \text{transonic} \quad \text{supersonic} \]

\[ DLR \]
Virtual Product in Aeronautics
Simulation Based Certification

Status
- A/C Certification relies mainly on physical tests
- In some cases, certification is supported by simulation (e.g. flutter)

Future
- Simulation Based Certification
- Validated virtual testing procedures
- Comprehensive virtual product analysis
  - in particular in limit cases

Requirements
- Improvement of simulation reliability
- Software and certification standards
- Close collaboration with authorities