Controlled Flight Beyond Stall

The X-31 Aircraft Program

AoA<=70°

24° landing
Lilienthal Hanggliding (1894)
Nine months after the crash of the Birgenair 757 off the coast of the Dominican Republic, the official accident report was published on November 8. The document states that the main reason for the disaster, which cost the lives of 178 passengers and 11 crew, was the failure of the crew to interpret the signs of impending stall correctly and act accordingly. The pilots were confused by false speed displays due to a blocked pitot.

Hannes Ross
Samara, May 2007
Military Accidents

STALL / SPIN OUT - OF - CONTROL
OPERATIONAL ACCIDENTS
1965 - 1986

Total losses (fighter / attack, bomber, trainer, etc): 566
Fatalities per accident: 0.85

<table>
<thead>
<tr>
<th>Fighter / Attack</th>
<th>USAF</th>
<th>USN</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-4</td>
<td>68</td>
<td>F-4</td>
</tr>
<tr>
<td>F-100</td>
<td>30</td>
<td>A-4/TA-4</td>
</tr>
<tr>
<td>F-111</td>
<td>17</td>
<td>F-8</td>
</tr>
<tr>
<td>A-7</td>
<td>14</td>
<td>A-7</td>
</tr>
<tr>
<td>F-5</td>
<td>10</td>
<td>EA-6</td>
</tr>
<tr>
<td>F-15</td>
<td>10</td>
<td>F-14</td>
</tr>
<tr>
<td>A-10</td>
<td>8</td>
<td>T-2</td>
</tr>
<tr>
<td>F-16</td>
<td>5</td>
<td>A-6</td>
</tr>
</tbody>
</table>

Total value of fighter / attack losses: $3.95 Billion
Hannes Ross
Samara, May 2007

Poststall Landing Gear, Grashopper, 1973
Lift vs. Angle of Attack

Maximum Lift

Lift Curve

Stall Region

X-31 Poststall-Regime

Normal Flight Regime

Flight Path

Angle of Attack (AOA)

0° 30° 60° 90°

Dr. Wolfgang Herbst
Results from Manned Close-in Combat Simulations at IABG, Germany 1979

<table>
<thead>
<tr>
<th>No. of Engagements:</th>
<th>SRM + GUN: 331</th>
<th>Gun only: 125</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Time to first firing possibility</td>
<td>SRM + GUN: 2:1</td>
<td>2,5:1</td>
</tr>
<tr>
<td></td>
<td>SRM: 2:1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GUN: 8:1</td>
<td>10:1</td>
</tr>
<tr>
<td>3. Engagement wins</td>
<td>5,4:1</td>
<td>4,2:1</td>
</tr>
</tbody>
</table>
Flow Pattern, Water Tunnel
1. Design, develop, build two “low cost” demonstrator aircraft

2. Demonstrate the technical feasibility of Post-Stall maneuvering

3. Demonstrate the tactical utility of Post-Stall capability
Trailing Edge Trim Power vs. Angle of Attack

Angle of Attack (Deg)

DCM

-40°

-30°
Canard Pitch Moment vs. Angle of Attack
Rudder Effectiveness vs. Angle of Attack
Side Force Generation by Thrust Vectoring System

Hannes Ross
Samara, May 2007
X-31 TV Vane Arrangement
Thrust Vectoring Control Authority

- Improved control authority provides increased safety
- Eliminates inherent design problems such as deep-stall
- Provides for higher yaw acceleration to reduce departures/allow for graceful exit from spin
- Allows for unique entry conditions for additional emergency training
PST Flight Test Milestones

- 70 degree AoA, Steady State Flight

- Dynamic Entry
  M = 0.9
  AoA = 2 degrees

- Velocity Vector Roll (70 degree AoA)

AoA = 70 degrees
High Angle of Attack Manoeuvring

- Velocity Vector Roll
- Deceleration
## Close-in Combat Effectiveness: Simulations vs. Flight Test

### 1979 Simulation Results

<table>
<thead>
<tr>
<th></th>
<th>Guns + SRM</th>
<th>Guns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engagement Wins</td>
<td>5.4:1</td>
<td>4.2:1</td>
</tr>
</tbody>
</table>

### Flight Test Results, 1994

- **X-31 with PST**
- **X-31 w/o PST**
- **F-18 Exchange Ratio**
- **X-31 Exchange Ratio**
**Objective**

- ESTOL experiments shall demonstrate a reasonable, minimum energy during touch-down and landing

**Concept**

- High Angle of Attack (AoA) Approach using Thrust Vectoring for Precise Low Speed Control
- Derotation to Land (Reduced Pitch Angle)
- Thrust Vector-Assisted Rotation for High AoA Fly-Away
Natural and Man-Made Landing Approach
Data Sharing with Universities, Institutions:

- AC Geometry for CFD calculations
- AC Geometry for WT modell
- Trajectory optimization Well, Stuttgart
- FCS design, Uni Stuttgart
- DLR, program participation, Parameter identification
# X-31 Experimental Aircraft - Exploitation of Configuration and other Project-relevant Data in external Cooperations

<table>
<thead>
<tr>
<th>Project</th>
<th>Description</th>
<th>Main Partners</th>
<th>X3 I - Data used</th>
<th>RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frontier</strong></td>
<td>EU Research Project on development and verification of multidisciplinary</td>
<td>BAe Systems, EADS M, Univ.</td>
<td>Wing lofting</td>
<td>Multipoint optimisation of dimensioning of wing, t.c. flaps for supersonic roll performance</td>
</tr>
<tr>
<td></td>
<td>optimisation methodologies</td>
<td>of Trieste, Univ. of Newcastle</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>JULIUS</strong></td>
<td>EU Research Project on development and verification of multidisciplinary</td>
<td>BAe Systems, EADS M, Dassault</td>
<td>Complete Aircraft CAD Model</td>
<td>Test of CAD-repair procedure, Aeroelastic Simulation of flight manoeuvres (e.g. rapid roll, 5g pull up)</td>
</tr>
<tr>
<td></td>
<td>simulation analysis tools in HPC environment</td>
<td>Aviation – Univ. of Swansea</td>
<td>Structural models of wing and of complete aircraft</td>
<td></td>
</tr>
<tr>
<td><strong>FASTFLO II</strong></td>
<td>EU-Research project on development and verification of fast CFD analysis</td>
<td>NLR, DLR, EADS-M, Saab, FFA</td>
<td>Complete Aircraft CAD Model</td>
<td>Simulation of flow characteristics at high angle of attack by an unstructured Navier–Stokes solver</td>
</tr>
<tr>
<td></td>
<td>tools</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TA15</strong></td>
<td>EU research project on vortex flow phenomena</td>
<td>NLR, EADS-M, Alenia, DERA</td>
<td>Complete Aircraft CAD Model</td>
<td>Validation of CFD Methodology wrt to unsteady vortical flow phenomena</td>
</tr>
<tr>
<td>(proposed)</td>
<td></td>
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</tbody>
</table>
PREDICTION OF THE UNSTEADY BEHAVIOR OF MANEUVERING AIRCRAFT BY CFD AERODYNAMIC, FLIGHT-MECHANIC AND AEROELASTIC COUPLING

The main objective of this paper is to focus on the necessity for developing an interactive, multidisciplinary engineering tool for predicting the unsteady critical states of complex maneuvering aircraft. Such a simulation environment has to bring together aerodynamics, aeroelasticity and flight mechanics in a time-accurate simulation tool. In order to deliver such a tool in the near future, the DLR Project SikMa-"Simulation of Complex Maneuvers" has been initiated to combine these three disciplines into one simulation environment [18][19].

Figure 14: 3D flow field over the X-31 configuration at 18° angle-of-attack.
X-31, Eurofighter, und Tornado, Paris 1995
END
Reserve Slides
Thrust Vectoring for Civil Aircraft?

• T/W ratio for commercial aircraft: 0.25 – 0.35
• Primarily wing mounted engines: no lever arm for pitch and yaw
• Fixed engine nozzle, no variable exit area

Application of TV for commercial aircraft doubtful. Blended Wing body concepts could offer a new opportunities.
Program Pay-off’s

Development/Demonstration of new technologies:

- Application of the CCV F-104 approach to control law development
- Fully integrated thrust vectoring into the digital FCS System
- Pathfinder for the NARMCO carbon fiber material for the EF
- Opening of a new flight regime: Post Stall Arena
- Demonstration/evaluation of new operational capabilities (PST for CIC)
- Demonstration of precision short field landing techniques
- Development of a microminiaturized Air Data System

Development and Test of a new aircraft

- Training of a new generation of engineers from conceptual design through flight test

Development of a Vector nozzle for the EJ 200 engine by ITP in Spain
What we did not (yet) achieve:

- **Thrust Vectoring For Eurofighter**
  - Eurofighter
  - F-22
  - Su-30MKI with 3-D Nozzle
  - 2005 MIG-29 OVT With TV nozzles

But the Competitors have TV already!
Elements of the VECTOR Program

ESTOL
Extremely Short Take-Off and Landing

TAILLESS
Reduced Tail/Tailless

Thrust Vectoring
Vanes developed for the X-31 EFM program

AADS
Advanced Air Data System
Options for High Alfa Landing

High attitude
Normal approach angle
Low speed
Normal sinkrate
**High Thrust**

Normal attitude
Steep approach angle
Low speed
**High sinkrate**
"Low" Thrust
How Do We Maintain the Knowledge Base?
(US Data)

Source: Rand Corporation
Consolidation of European Aerospace Industry !?

EWADE

British Aerospace

Saab

Finmech.

EADS

Dassault

Hawker Siddeley

De Havilland

Hunting

Bristol

SIA Marchetti

Selenia

Aeritalia

Alenia

EFIM (Incl. Agusta)

Aermacchi

MBB

Dornier

TST

DASA

Casa

Aérospatiale

Matra

Dassault

Gripen Export

Grammar check is not always necessary.
EU Aerospace Industry

Turnover * and Employment *

[Graph showing turnover and employment from 1980 to 2002.]

Source: AECMA

*) based on EU consolidated turnover
[] inc. estimates for Sweden until 1992 and non-AECMA companies until 1996
Stall (2 Dimensional Calculations)
Evolution of Thrust/Weight Ratio
Fighter and VTOL Aircraft
Das Langbein Fahrwerk
Configuration Selection
Full Scale Thrust Vectoring Test

Samara, May 2007
Vane Manufacturing

Gewicht der C/C Ablenkschaufel: 6kg
Gewicht der Metallstruktur: 10kg

Vane 1 after Green Core Process

Delamination after first Carbonization process

Thrust Vector Vane Delaminations
Comparison X-31 vs. F-18 HARV
X-31, Thrust Vector Vane Attachment Scheme
Drove Aft Fuselage Changes

Booms for Vane Attachment and Actuation

Initial Flight Configuration: No booms!

Added Trim Surface

Hannes Ross
Samara, May 2007
Nosecone Strakes

Hannes Ross
Samara, May 2007