Knowledge-based Aircraft Systems Integration

Raghu Chaitanya Munjulury, Ingo Staack, Petter Krus
Linköping University, SE-58183, Linköping, Sweden
Agenda

• Introduction
  – Framework
• Objective
• Systems Integration
  – Flight Control System Integration
    • Actuator Sizing
    • Control Surfaces Integration
  – Fuel systems
  – Landing gear integration
• Conclusions
• Future work
CADLab: Conceptual Aircraft Design Laboratory

Concept Design

Preliminary Design

Detail Design

Blank Sheet/Requirements

Matlab(Tango)

CATIA(RAPID)

Preliminary Design
Knowledge-Based Geometry Design

Aircraft Sizing
XML Database
Dynamic Model

Aerodynamic Model
Structural Model
Control Surfaces

Engine Design
Geometric Model
Winglets and Tip Devices

Windshield and Fairings

Interior Design
Cabin and Pilot Layout

RAPID

Link inside CATIA
Link outside CATIA
Knowledge-Based Geometry Design
Framework Distribution

Model Fidelity Levels
- High
- Medium
- Low

Geometry
- RAPID
- Tango / RAPID
- BeX / RAPID

Systems
- RAPID
- Tango / RAPID
- Empirical calculations

Aero
- FineOpen / Ansys
- Tornado
- BeX

Structures / Weights
- CATIA / Ansys
- RAPID / Tornado
- Empirical calculations

Noise & Emissions
- Hopsan L-I

Stability & Control
- Hopsan L-I
- BeX / Tornado

Conventional Design
- Preliminary Design
Objective

- To investigate the early design stages to define the aircraft systems integration.
- A knowledge-based parametric definition of different aircraft systems: FCS, Fuel system, Landing gear
- Use parameters to modify the general layout of the system.
- Measure variables used in conceptual design.
Flight Control System Integration

- Simplifications and Assumptions
  - Systems symmetry
  - Valves omission
  - Positioning of the flight control system
  - Flight control system
  - Routing
  - Hydraulic Power Assembly
  - Geometry simplicity
# Flight Control System Integration

## Hydraulic Circuit Basic Components

<table>
<thead>
<tr>
<th>NAME</th>
<th>QUANTITY</th>
<th>FUNCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic Pump</td>
<td>2/system</td>
<td>It generates the hydraulic pressure which will power the actuators.</td>
</tr>
<tr>
<td>Hydraulic Tank (Reservoir)</td>
<td>1/system</td>
<td>It stores the hydraulic fluid which transmits power within the circuit.</td>
</tr>
<tr>
<td>Regulating valve of the pump</td>
<td>2/system</td>
<td>It regulates the hydraulic fluid flow.</td>
</tr>
<tr>
<td>Hydraulic Accumulator</td>
<td>1/system</td>
<td>It stores hydraulic fluid which will be used in case of emergencies.</td>
</tr>
<tr>
<td>Hydraulic conductors</td>
<td>N/A</td>
<td>They transfer the hydraulic fluid between components.</td>
</tr>
<tr>
<td>APU</td>
<td>1</td>
<td>It generates the hydraulic pressure which will power the actuators.</td>
</tr>
</tbody>
</table>

## Power and Control Units

<table>
<thead>
<tr>
<th>NAME</th>
<th>QUANTITY</th>
<th>FUNCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARTCU</td>
<td>3</td>
<td>Deflection control unit.</td>
</tr>
<tr>
<td>Power Unit</td>
<td>1/actuators path</td>
<td>It powers a set of actuators.</td>
</tr>
<tr>
<td>Actuator Drive Assembly</td>
<td>1/actuator</td>
<td>It controls a specific actuator.</td>
</tr>
<tr>
<td>Electric Drive Unit</td>
<td>1</td>
<td>It powers slats rotary actuator.</td>
</tr>
</tbody>
</table>

## Hydraulic Actuators

<table>
<thead>
<tr>
<th>NAME</th>
<th>QUANTITY</th>
<th>FUNCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slats</td>
<td>1/surface</td>
<td>Rotary actuator which extends slats in the leading edge.</td>
</tr>
<tr>
<td>Ailerons</td>
<td>1/surface</td>
<td>It deflects ailerons' control surface.</td>
</tr>
<tr>
<td>Elevators</td>
<td>1/surface</td>
<td>It deflects elevators' control surface.</td>
</tr>
<tr>
<td>Rudder</td>
<td>1/surface</td>
<td>It deflects rudder's control surface.</td>
</tr>
<tr>
<td>Flaps</td>
<td>1/surface</td>
<td>It deflects flaps' control surface.</td>
</tr>
<tr>
<td>Spoilers</td>
<td>1/surface</td>
<td>It deflects spoilers' control surface.</td>
</tr>
</tbody>
</table>
Sizing - EHA

- Actuators based on an electric motor driven pump connected to a hydro-cylinder
- 5 main components: hydraulic cylinder, pump, motor, accumulator and power electronics
- Power electronics and accumulator size determined by their cooling surface, being considered as a cuboid
- It is assumed that motor and pump are on the same axis parallel to the cylinder
Sizing - EHA

- The previous values and the table below (estimated statistically) allow to have a preliminary sizing of an EHA, depending on the value of the constants. With the dimensions of existing EHAs components it is possible to define those values.

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameters</th>
<th>Dimension Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder</td>
<td>piston diameter $d_Z$,</td>
<td>$h_{Zyl} \approx k_0 + k_1 d_Z$</td>
</tr>
<tr>
<td></td>
<td>stop-to-stop stroke</td>
<td>$b_{Zyl} \approx k_2 + k_3 \frac{d_Z^2}{h_{Zyl}}$</td>
</tr>
<tr>
<td></td>
<td>$x_{\text{max}} - x_{\text{min}}$</td>
<td>$l_{Zyl} \approx k_4 + k_5 (x_{\text{max}} - x_{\text{min}})$</td>
</tr>
<tr>
<td>Axial piston pump</td>
<td>geometric displacement $V_{g,\text{max}}$,</td>
<td>$l_P \approx k_0 \lambda_P^2 \frac{2}{\sqrt{1 + k_1 V_g}}$</td>
</tr>
<tr>
<td></td>
<td>typical $\frac{l_P}{\sqrt{A_P}} =: \lambda_P$, $A_P = b_P \cdot h_P$</td>
<td>$d_P \approx 2 \sqrt{\frac{A_P}{\pi}} = 2 \frac{l_P}{\sqrt{\pi} \lambda_P}$</td>
</tr>
<tr>
<td>AC induction /</td>
<td>nominal torque $M_{\text{mot,\text{nom}}} := \frac{P_{\text{mot,cont}}}{n_{\text{mot,\text{max}}}}$</td>
<td>$V_{\text{mot}} = \frac{\pi}{4} d_{\text{mot}}^2 l_{\text{mot}}$</td>
</tr>
<tr>
<td>brushless DC motor</td>
<td></td>
<td>$V_{\text{mot}} \approx k_0 M_{\text{mot,\text{nom}}}^{k_1}$</td>
</tr>
</tbody>
</table>

Figure 2. Large EHA
Sizing - EMA

• Actuator where a mechanical gearing is used to couple an electric motor to a flight control surface.

• Aerospace EMA major components: Brushless motor (cylindrical or annular); Gearbox, Spur gear or Cycloidal reducer; ball or roller screw, Spherical, axial or radial load bearing

• Main design model: Scaling laws
Scaling Laws

• Scaling laws evaluates the effect of varying parameters of a component compared to a known reference

• Scaling ratio of a parameter: \( x^* = \frac{x}{x_{\text{ref}}} \)

• 2 main assumptions:
  – All material properties are identical to those of the reference
  – The ratio of all the lengths of the considered element to all the lengths of the reference component is constant

• Parameters representing geometric quantities can be directly obtained from the assumption of geometric similarity: \( V^* = l^*^3 \), \( M^* = l^*^3 \)

Flight Control Systems Integration
Control Surfaces Integration

Plain
Slotted
Split
Zap
Fowler
Double Slotted
Double Slotted Flap with leading edge slat
Aircraft fuel Systems - Method

- Description

A Knowledge Based Engineering (KBE) approach was used to define the system:

- Reusable information is previously defined and then automatically instantiated in a new environment with new inputs.
- User Defined Features contain flexible and parametric component models.
Method

- Simplifications

• All geometries are symbolic, representing a space allocation inside the aircraft for the fuel system. A realistic representation of real components can be realized in detail design.

• Smaller geometries such as valves or fuel intakes inside the tanks are not represented/modelled.

• The fuel quantity measuring system is not included.

• Symmetry is applied in the whole system, but both sides are represented.

• Fuel tubing or piping is represented with direct lines between two pumps or tanks and represent the minimum length needed for this component. An exception for this is the pipe connecting fuel tanks from the tail to the fuselage, which is represented with more detail.

• Wing and horizontal stabilizer spars are represented as surfaces limiting the tanks.
Method - Work flow

Definition of the fuel tanks

Definition of the engine feed system

Definition of the fuel transfer system

Crossfeed piping

Connect feed pumps according to the feed system layout

Fuel transfer piping

Connect all tanks, adapting to the different tanks layout

Flexible tank layout: number of tanks, position and shape

Feed system layout depending on engines: select feed tanks and define engine boost pumps
Functions implemented

- Wing Tanks
- Fuselage Tanks
- HT Tanks
Functions implemented

- Feed pumps and tanks arrangement for 1 to 4 engines configuration.
- Centrifugal feed pumps (most common) of 3 types:
  - Skin mounted.
  - Cartridge-cannister.
  - Spar mounted.
- Redundancy selectable.
- Crossfeed piping selectable.

- Engine feed
Functions implemented - Fuel transfer

Crossfeed piping shown in orange; connecting four feed tanks with pump redundancy. Transfer piping is shown in green, including the aircraft's refuel station.

3-engines configuration with 3pointPiping
Results

Boeing 777-200 fuel tank arrangement

Representation of B777-like fuel systems in RAPID
Results

A340- 500 like fuel representation
Fuel System Analysis

- The modeled fuel system can be used for enhanced center of gravity analysis. One important objective is the shift of the center of gravity due to the aircraft attitude (bank, roll, yaw) and accelerations in combination with the filling level of each tank.

- Surrogate models of the weight and center of gravity are created for every tank on the total system level.
  - These surrogate models may be used to study the center of gravity shift due to different filling-/emptying patterns, enabling the development (and inclusion) of a behavioral model for the fuel system.
  - A discrete mission point analysis on an enhanced conceptual aircraft design level, enabling a higher fidelity than normally applied in this stage of development which can be used to study the effects of a reduced stability or unstable configurations.
  - With the availability of the surrogate tank models and the behavioral concept, the fuel system can easily incorporated in other component based simulations (such as Modelica or Hopsan), enabling a very efficient way of detail investigations of the fuel system.
Introduction

- Paul R. Kraus shows a way to compute an analytical approach using bending moments in the LANGE program. His conclusion is that results obtained using an analytical method are more sensitive. Robert H. Wille describes how the LANGE program operates and modified it to extend its database to consider unconventional landing gears.

\[
P_v = \frac{W - V_0}{K_2 (S \cos \theta)} - K_1 W (S \cos \theta)
\]

where:

- \( W \) = static
- \( g = 32.17 \)
- \( V_0 \) = sink
- \( K_1 = (1.0) \)
- \( S \) = total
- \( \theta \) = angle
- \( K_2 \) = gear


Objectives for Case Study

- To study F-15 Eagle, F-16A, T-45A, and AV-8B (point-to-point analysis was performed to find the loads applied in the structure, Previous studies carried out by McDonnell Douglas [(Kraus, 1970), (Willie, 1989)]

- In the present study, a bending moment analysis is used to find out the loads affecting the structure and be able to compute the weight.
  - For bending moment analysis, landing gears have been simplified, the most important components such as pistons and main bars are considered.
  - The simplification also includes avoiding small bars and other components that do not take part in the load analysis.
Load Cases

- Two/Three Point Landing (Case 1)
- Tail Down Landing (Case 2)
- Lateral Drift Landing (Case 3)
- Braked Roll (Case 4)
- Ground Turning (Case 5)
- Pivoting (Case 6)
Analytical Development

• The structural simplification of the models is made in order to ease the mathematical approach. (F-15 E, F-16A, T-45A, and AV-8B )
  – External reactions calculation
  – Bending moments calculation
  – Tubes sizing
  – Weight calculation
Analytical Development - *External reactions* - T-45A
Analytical Development - *External reactions* - T-45A

- The structure is simplified in the front view by ignoring the existence of a drag brace and replacing it by an applied force directly into the main vertical bar.
- The bar that links the drag brace with the main bar that is used to guide the rotation of the landing gear is substituted by an all degree of freedom restriction. With respect to the side view, the model is considered as a cantilever.

\[
\begin{align*}
\Sigma F_x &= 0 \rightarrow R_{1_x} + D = 0 \rightarrow R_{1_x} = -D \\
\Sigma F_y &= 0 \rightarrow -R_{1_y} + V = 0 \rightarrow R_{1_y} = V \\
\Sigma M_A &= 0 \rightarrow M_{A_1} = D \cdot \cos(\gamma_1) \cdot l_1 + V \cdot \sin(\gamma_1) \cdot l_1
\end{align*}
\]

Note: For cases 4 to 6, \( l_1 \) refers to:
\[
l_1 = l_1 - \frac{s \cdot f}{\cos(\gamma_1)}
\]

- Side View

\[
\begin{align*}
\Sigma F_y &= 0 \rightarrow R_{1_y} = -S - F_2 \cdot \sin(\phi_1) \\
\Sigma M_B &= 0 \rightarrow F_2 = \frac{S \cdot l_2 + V \cdot (l_3 + l_5)}{l_3 \cdot \sin(\phi_1)} \\
R_{2_y} &= F_2 \cdot \sin(\phi_1) \\
R_{2_x} &= F_2 \cdot \cos(\phi_1) \\
l_2 &= l_2 - (s \cdot f)
\end{align*}
\]

Note: For cases 4 to 6, \( l_2 \) refers to:
the relation between the external cylinder and the piston need to be kept in mind, each element is sized, different bending moments are taken into consideration.

- Front View. Vertical Loads

\[ M_{1_{\text{vert}}} = M_{1_{\text{h-vert}}} - M_{2_{\text{vert}}} = M_{3_{\text{vert}}} - M_{4_{\text{vert}}} = V \cdot l_3 \]

- Front View. Side Loads

\[ M_{1_{\text{side}}} = S \cdot (l_2 - l_6) \\
M_{2_{\text{side}}} = S \cdot (l_4 + s) \\
M_{3_{\text{side}}} = M_{3_{h-side}} = S \cdot l_4 \\
M_{4_{\text{side}}} = 0 \]

Note: For cases 4 to 6, \( s \) and \( l_2 \) refer to:

\[ s = s \cdot (1 - f) \]

\[ l_2 = l_2 - (s \cdot f) \]

- Side View. Vertical Loads

\[ M_{1_{\text{side}}} = V \cdot \sin(\gamma_1) \cdot l_1 \\
M_{2_{\text{side}}} = V \cdot \tan(\gamma_1) \cdot (l_4 + s) \\
M_{3_{\text{side}}} = V \cdot \tan(\gamma_1) \cdot l_4 \]

- Front View. Drug Loads

\[ M_{1_{\text{drug}}} = D \cdot \cos(\gamma_1) \cdot l_1 \\
M_{2_{\text{drug}}} = D \cdot (l_4 + s) \\
M_{3_{\text{drug}}} = D \cdot l_4 \]

Note: For cases 4 to 6, \( s \) and \( l_1 \) refer to:

\[ s = s \cdot (1 - f) \]

\[ l_1 = l_1 - \frac{s \cdot f}{\cos(\gamma_1)} \]
Based on the length and inner diameter information, the outer diameter is sized.

It is clear that the inner diameter of the external cylinder needs to be equal to the outer diameter of the piston. Therefore, the piston has to be sized first by letting the user input the desired inner diameter.

The external cylinder is sized after the outer piston diameter is obtained.

If the length and the inner diameter of a tube are known, the elastic section modulus formulas of a hollow cylinder can be used so as to obtain the outer diameter.

As the equations are of 4th order, there are four possible solutions. Two of them always have an imaginary part, therefore they can be discarded. The other two solutions may or may not have an imaginary component. The chosen solution is the minimum real value without the imaginary part.

Once the outer diameter is obtained, the area of the tube can be calculated.
Analytical Development - Weight calculation

- The area and the length of the tube are known, the volume can be easily obtained

\[ \text{Volume} = \text{Area} \cdot \text{Length} \]

- Finally, using the definition of density, the weight of the bar is

\[ \rho = \frac{\text{Mass}}{\text{Volume}} \quad \rightarrow \quad \text{Mass} = \rho \cdot \text{Volume} \]
Overview of Implementation

MS EXCEL
- Model Selector
  - Open Geometry Builder
  - Update
- Active Workbook

CATIA V5
- Models Database
- Updated Measures
- Updated Coordinates

Diagram showing the flow between MS EXCEL and CATIA V5, indicating how data and updates are communicated between the two systems.
Overview of Implementation – Main Layout
Overview of Implementation - Main Layout Cont.
Overview of Implementation – Reaction (left) and Bending Moments (right)

**Cases:**
- **Case 1 & 2:** Two/three point level landing ($V \neq 0, D \neq 0, S = 0$)
- **Tail Down Landing:** ($V = 0, D \neq 0, S = 0$)

**Parameters:**
- $R_A$
- $M_{LA}$
- $M_{RB}$
- $R_{f}$
- $R_{r}$

**Moments:**
- $M_{max}$
- $M_{y}$
- $M_{z}$

**Units:**
- N
- mm
- mm
- N

**Examples:**
- $M_{LA} = 5904.08$ N-mm
- $M_{RB} = 5904.08$ N-mm

**Results and Forces:**
- $F_{x}$
- $F_{y}$
- $N$

**Examples:**
- $F_{x} = 1000.00$ N
- $F_{y} = 0.000$ N

**Moments Table:**

<table>
<thead>
<tr>
<th>Bar</th>
<th>$M_{y}$</th>
<th>$M_{z}$</th>
<th>$M_{x}$</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5000</td>
<td>0000</td>
<td>5000</td>
<td>N-mm</td>
</tr>
<tr>
<td>2</td>
<td>5000</td>
<td>0000</td>
<td>5000</td>
<td>N-mm</td>
</tr>
</tbody>
</table>

**Schematic Diagrams:**
- Front View
- Side View
- Reaction Forces
- Bending Moments
Overview of Implementation – Cross-section Area and Weight
Conclusion - FCS

• *Fast realisation of the concept*
• *To support Conceptual to Preliminary Aircraft Design*
• Specialized tool for specialized needs (full CAD env.)
• Coupling to for CFD analysis for all lifting surfaces
• Flexibility level
  – Characteristic parameter
  – It allows to tailor connections between hydraulics systems and flight control surfaces
  – Representation widely used in the industry
Conclusions – Fuel system

- Enabled fuel capacity estimation based on 3D geometries; an estimation that is specially complex when working with integral tanks.
- The possibility to accurately position tanks and pumps in a fast way, with the objective to be able to work with the tool in both, conceptual and preliminary design phases. A feature that can be used, for example, for space allocation or systems integration in early design stages.
- Measurement of piping or tubing length for a simple example of transfer system architecture; a first estimation that can be a relevant data for pump sizing.
- Attitude dependent fuel distribution (influence of center of gravity) of partially filled tanks. This feature can help to position pump inlets and venting points and to analyze the fuel influence in aircraft’s center of gravity and stability.
- Automation and parametric description of the system layout. Together with the former topic, this enables a export of the system to other (simulation) program for further, more detailed system analysis.
Conclusions – Landing Gear

• The procedure developed is able to compute the weight of the existing bars for a particular landing gear disposition.

• Support the designer both with a numeric and a graphical results. The computations keeps the user at all times in touch with a visual perspective on where the points are placed and the overall disposition of the bars.

• The results obtained by the bending moment process are satisfactory. The results are really close from the ones found in the studies done by (Kraus, 1970) and (Willie, 1989).

• Limitations when using the procedure are that, the bars that can be sized, are the ones that receive moments from the applied loads. The procedure is able to size the main bars of the gears for the simplifications done. For other bars that take just forces, the method from previous studies can be used and added as an extension to the work presented.
Future Work: Simulation Model
Thank You

raghu.chaitanya@liu.se

www.liu.se