Verifying Integrated Motor, Drive and Control Systems

Mike Donnelly
Principal Engineer
System Modeling and Analysis

February 2013
Integrated System Simulation

**Physical Plant**
- Thermal
- Mechanical
- Hydraulic
- Aerodynamics

**Electrical**
- Analog, Digital, & Mixed-Signal circuits
- Electro-Mechanical

**Sensors & Actuators**
- Embedded Control or Supervisory
- Digital Control Micro-controllers
- Transfer functions

**Control**
Benefits of Integrated System Modeling and Simulation

- Enables “Virtual” System Integration, Analysis and Test

- Supports capture and re-use of design expertise and process know-how
  - Internal/External expert’s knowledge captured in an executable form
  - Quality and Reliability data and methods captured in model libraries and design flows

- Supports models at any level of abstraction, during any phase of the design process
  - High-level behavioral
  - Low-level implementation
  - “Mixed-level” verification
Aileron Motion Control Example

- “More Electric Aircraft” System Trade-Off (hydraulic actuator vs. BLDC motor)
  - Component sizing, selection
  - Control strategy selection, loop design
  - Requirements (power, speed, accuracy)

- Multi-tool Integrated System Modeling with SVX
  - Test program in LabVIEW
  - Control algorithm in Simulink
  - Electro-mechanical “plant” in SystemVision

- Detailed system implementation models (sensors, electronics)
  - Resolver angle sensor and signal conditioning
  - Control S/W, SVM (digital FPGA), H-bridge, FEA-based motor
  - Stress monitoring across all domains
Legacy System: Hydraulic Actuator with Electro-hydraulic Controls

Aileron Angle Control

Valve Spool Control

Electro-Hydraulic Valve

Hydraulic Lines

Motor-driven Pressure Reg. Pump

Actuator
Hydraulic System Performance

Command Angle

Actual Aileron Angle

Actuator Bottom-side Pressure

Actuator Top-side Pressure

Pump Motor Power

© 2012 Mentor Graphics Corp. Company Confidential
www.mentor.com
New “More Electric” Aileron Control System

Aileron Angle Control
(same as hydraulic system)

Field-Oriented Motor Controller (FOC)

Ideal BLDC Motor

Gear and simple mechanical dynamics
BLDC (PMSM) Motor Model in VHDL-AMS

--- Flux relationships

\[
\lambda_{as} = L \cdot (i_{as} - 0.5 \cdot i_{bs} - 0.5 \cdot i_{cs}) + \lambda_{max} \cos(\theta_{r, np}) \\
\lambda_{bs} = L \cdot (i_{bs} - 0.5 \cdot i_{as} - 0.5 \cdot i_{cs}) + \lambda_{max} \cos(\theta_{r, np} - \pi_2/3) \\
\lambda_{cs} = L \cdot (i_{cs} - 0.5 \cdot i_{as} - 0.5 \cdot i_{bs}) + \lambda_{max} \cos(\theta_{r, np} + \pi_2/3) \\
\]

--- Voltage relationships

\[
v_{as} = r_s \cdot i_{as} + \lambda_{as} \cdot \dot{i}_{as} \\
v_{bs} = r_s \cdot i_{bs} + \lambda_{bs} \cdot \dot{i}_{bs} \\
v_{cs} = r_s \cdot i_{cs} + \lambda_{cs} \cdot \dot{i}_{cs} \\
v_{sn} = r_s \cdot i_{sn} + \lambda_{sn} \\
\]

--- Torque and mechanical relationships

\[
\begin{align*}
t_e &= -1.0 \cdot \frac{\lambda_{as}}{r_s} \sin(\theta_{r, np}) + \frac{\lambda_{bs}}{r_s} \sin(\theta_{r, np} - \pi_2/3) + \frac{\lambda_{cs}}{r_s} \sin(\theta_{r, np} + \pi_2/3) \\
t &= -1.0 \cdot \dot{\theta} + d \cdot \psi + j \cdot \dot{\psi} \\
\theta_r &= \psi / \text{integral}; \quad \text{Assumes initial angle = 0.0 at time 0.} \\
\theta_{r, np} &= \theta_{r}(np_2).
\end{align*}
\]

end architecture linear_magnetics;
Inside the Field-Oriented Motor Controller (Graphical Model)

PI Control for D-Q Currents

Inverse Transformations for Voltages

Ideal DC to AC Sinusoidal Drive and Current Sensing

3-Phase to Alpha/Beta and D-Q Transformations for Currents

Ideal Rotor Angle Sensor Feedback
BLDC Actuation System Performance
(Compared to Hydraulic System)

- **Hydraulic System Aileron Angle**
- **BLDC System Aileron Angle**

**BLDC Motor Phase Currents**

**BLDC Motor Power**

< 300W (vs. 3.5kW for Hydraulic System)
BLDC Motor and Drive “Hardware” in SystemVision
(Connected to the Controller and the Test Program via SVX)

Drive Command coming from Simulink

Set Point coming from LabVIEW

Control Surface Angle sent to Simulink and LabVIEW

BLDC

FOC

Aileron
"PI" Aileron Controller in Simulink
(Connected to the "Hardware" and the Test Program via SVX)
Test Program (Block Diagram) in LabVIEW
(Connected to the "Hardware" and the Controller via SVX)
LabVIEW (Front Panel) Test Results Display w/ Measurements in SV Waveform Analyzer

Fail

Actual Aileron Angle

Aileron Command Angle

Delay, Overshoot and Settle-time Measurements

fail 3 fail 2 fail
Implementation-level
Aileron Control System Model

Discrete (sampled) FOC Algorithm

Space-Vector Modulation (SVM) Algorithm and Digital Switch Controller

3-Phase Bridge with Power MOSFETs, Gate Drive Circuits and Power Monitoring

FEA-generated BLDC model

Aileron

Mechanical Dynamics including “modal” Flexible Shaft

Resolve-to-Digital Shaft Angle Sensor
3-Phase Bridge
w/ MOSFET Switches and Power Monitoring

Page 1

Page 2

Power and Temperature Monitor

© 2012 Mentor Graphics Corp. Company Confidential
www.mentor.com
MotorSolve FEA-based Motor Design Tool
Generates Accurate VHDL-AMS Motor Models
Angle Sensor: Resolver-to-Digital Converter

N-bit A/D Converters (Integer Out)

Resolver

Tracking type Resolver-to-Digital Converter
Performance of Implementation-level System

- Aileron Command Angle
- Actual Aileron Angle
- Power Loss in Switching Bridge Circuit
- FEA Motor Phase Currents
- Torque in Center of Flexible Shaft
Automated Stress Analysis
Applied across Multi-Discipline Design Aspects

<table>
<thead>
<tr>
<th>Part Instances</th>
<th>Stress Ratios</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>flexible_shaft_stress1/segment_n</td>
<td>stress_ratio_torque</td>
<td>106.63%</td>
</tr>
<tr>
<td>flexible_shaft_stress1/segment_t</td>
<td>stress_ratio_torque</td>
<td>106.83%</td>
</tr>
<tr>
<td>flexible_shaft_stress1/segment_4/gen</td>
<td>stress_ratio_torque</td>
<td>106.70%</td>
</tr>
<tr>
<td>flexible_shaft_stress1/segment_2/gen</td>
<td>stress_ratio_torque</td>
<td>106.79%</td>
</tr>
<tr>
<td>flexible_shaft_stress1/segment_3/gen</td>
<td>stress_ratio_torque</td>
<td>106.74%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_b_p/dymosfet</td>
<td>stress_ratio_current_ids_avg</td>
<td>88.24%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_b_p/dydiode</td>
<td>stress_ratio_voltage_vrm</td>
<td>85.45%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_b_p/dymosfet</td>
<td>stress_ratio_voltage_vds</td>
<td>85.45%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_b_p/dydiode</td>
<td>stress_ratio_voltage_vds</td>
<td>85.45%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_a_p/dymosfet</td>
<td>stress_ratio_voltage_vds</td>
<td>85.42%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_a_p/dydiode</td>
<td>stress_ratio_voltage_vds</td>
<td>85.42%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_a_p/dymosfet</td>
<td>stress_ratio_voltage_vds</td>
<td>85.41%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_a_p/dydiode</td>
<td>stress_ratio_voltage_vds</td>
<td>85.41%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_a_p/dymosfet</td>
<td>stress_ratio_voltage_vds</td>
<td>85.12%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_a_p/dydiode</td>
<td>stress_ratio_voltage_vds</td>
<td>85.13%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_c_p/dymosfet</td>
<td>stress_ratio_current_ids_avg</td>
<td>83.12%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_c_p/dydiode</td>
<td>stress_ratio_current_ids_avg</td>
<td>83.12%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_c_p/dymosfet</td>
<td>stress_ratio_current_ids_avg</td>
<td>81.89%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_c_p/dydiode</td>
<td>stress_ratio_current_ids_avg</td>
<td>81.89%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_c_p/dymosfet</td>
<td>stress_ratio_rpower_avg</td>
<td>57.62%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_c_p/dydiode</td>
<td>stress_ratio_power_avg</td>
<td>57.62%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_c_p/dymosfet</td>
<td>stress_ratio_voltage_vgs</td>
<td>56.88%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_c_p/dydiode</td>
<td>stress_ratio_power_avg</td>
<td>56.88%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_c_p/dymosfet</td>
<td>stress_ratio_voltage_vgs</td>
<td>50.05%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_c_p/dydiode</td>
<td>stress_ratio_power_avg</td>
<td>50.05%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_c_p/dymosfet</td>
<td>stress_ratio_voltage_vgs</td>
<td>50.05%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_c_p/dydiode</td>
<td>stress_ratio_power_avg</td>
<td>50.05%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_c_p/dymosfet</td>
<td>stress_ratio_voltage_vgs</td>
<td>50.02%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_c_p/dydiode</td>
<td>stress_ratio_power_avg</td>
<td>50.02%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_c_p/dymosfet</td>
<td>stress_ratio_voltage_vgs</td>
<td>50.02%</td>
</tr>
<tr>
<td>h_bridge_l_mon_mosfet1/xpwr_sw_c_p/dydiode</td>
<td>stress_ratio_power_avg</td>
<td>50.02%</td>
</tr>
</tbody>
</table>

Flexible Shaft Torque Exceeding Rated Value
MOSFET and Diode Currents and Voltages: Small Margin
Other Part Ratings have margin, some excessive (i.e. Could use lower cost part in some cases?)
Summary

- "Virtual" System Integration:
  - Mechanical/Aero
  - Motors, sensors, hydraulics
  - Power and small signal electronics
  - Controls and software

- Supports capture and re-use of design expertise and process know-how
  - Expert’s aerodynamics knowledge captured in an executable form
  - Reliability stress data captured in models, with automatic extraction

- Simulate at any level of abstraction, during any phase of the design process