Modelling and Simulation Specialists

**Multi-Domain Simulation of Hybrid Vehicles**

Multiphysics Simulation for Autosport / Motorsport Applications Seminar

UK Magnetics Society
Claytex Services Limited

Software, Consultancy, Training

• Based in Leamington Spa, UK
  – Office in Cape Town, South Africa
• Experts in Systems Engineering, Modelling and Simulation
• Business Activities
  – Engineering consultancy
  – Software sales and support
  – Modelica library developers
  – FMI tool developers
  – Training services
    • Dassault Systemes Certified Education Partner
• Global customer base
  – Europe, USA, India, South Korea, Japan
Challenges

• Market demands
  – Improved fuel economy
  – Lower emissions
  – Improved reliability
  – Noise quality
  – Driveability
  – Performance

• Engineering solutions
  – More active systems
    • Increases complexity
  – Better control of existing systems
    • Increasingly complex control requiring large calibration effort
  – Tighter integration of all vehicle systems
  – Hybridisation of powertrain

• Management demands
  – Faster time to market
  – Lower development and manufacturing cost
Vehicle Modelling

- Engine
  - Air flow
  - Mechanics
  - Cooling system
  - Fuel system
  - Control system
  - Electrification
  - Hydraulics

- Gearbox and Driveline
  - Mechanics
  - Thermal
  - Hydraulics
  - Electrification
  - Control
  - Cooling

- Thermal Management
  - Engine Cooling
  - HVAC
  - Battery Cooling
  - Power Electronics Cooling

- Battery
  - Electrical
  - Thermal
  - Cooling
  - Control

- Chassis
  - Mechanics
  - Active systems
  - Control

- Electric Drives
  - Electrical
  - Magnetic
  - Thermal
  - Control
The need for physical modelling

• Automotive products are complex systems covering many domains
  – Mechanical, Electrical, Hydraulic, Pneumatic, Thermal, Chemical, Control, Magnetic, …

• No longer sensible to wait for prototypes to verify that all these systems interact in a good way

• It’s not practical, or perhaps even possible, to fully verify and validate control systems using prototypes

• Need to use predictive models and not just functional ones to make simulation useful for control development from an early stage of the project
Functional and Predictive models

- A Functional model is one that captures the key function of the model
- A Predictive model allows us to predict the behaviour and explore its characteristics

- The clutch is there to make sure the two inertias rotate at the same speed when engaged
- Functional model
  - Would reduce the relative speed across the clutch in a predefined manner
  - The controlling parameter would be the engagement time
- Predictive model
  - Would include a model for friction and the torque transfer would be a function of the clutch clamp load, relative speed, temperature, …
  - The parameters would include the geometry and friction characteristics
  - The engagement time could be predicted under different operating scenarios
Dymola

- Multi-domain modelling and simulation tool using a component orientated, physical modelling approach
  - Mechanics (1D, MultiBody), 1D Thermofluids, Control, Thermal, Electrical, Magnetics and more
- Promotes extensive model reuse at component and system level
  - Components represent physical parts: valves, gears, motor
  - Connections between parts describe the physical connection (mechanical, electrical, thermal, signal, etc.)
- Store your own component and system models in libraries to easily share and reuse them across the business
Model Definition

• Models are defined using the Modelica modelling language
  – A freely available, open source, generic modelling language
  – Design for convenient, component orientated modelling of complex multi-domain systems
  – Developed by the Modelica Association
    • An independent, international not-for-profit organisation

• Dymola provides access to the Modelica code behind models

```modelica
model Inertia
  extends Interfaces.Rigid;
  parameter SI.Inertia J=1 "Moment of Inertia";
  SI.AngularVelocity  w "Angular velocity";
  SI.AngularAcceleration a "Angular acceleration";
  equation
    w = der(phi);
    a = der(w);
    flange_a.tau + flange_b.tau = J * a;
end Inertia;
```
Modelling Magnetics in Dymola

• Two libraries available within the Modelica Standard Library covering magnetics
  – Flux Tubes
    • for modelling of electromagnetic devices with lumped magnetic networks.
    • suited for both rough design of the magnetic subsystem of a device as well as for efficient dynamic simulation at system level together with neighbouring subsystems
    • Typical applications are actuators and inductors
  – FundamentalWave
    • for modelling of electromagnetic fundamental wave models for the application in multi phase electric machines
    • All the machine models provided in this library are equivalent two pole machines. The magnetic potential difference of the connector therefore also refers to an equivalent two pole machine
    • In machines with more than three phases only effects of currents and voltages on the magnetic fundamental waves are considered
Motor models

• Basic concept
  – The exact magnetic field in the air gap of an electric machine is usually determined by an electromagnetic finite element analysis
  – The waveform of the magnetic field, e.g., the magnetic potential difference, consists of a spatial fundamental wave - with respect to an equivalent two pole machine - and additional harmonic waves of different order.
  – The fundamental wave is however dominant in the air gap of an electric machine
  – In the fundamental wave theory only a pure sinusoidal distribution of magnetic quantities is assumed. It is thus assumed that all other harmonic wave effects are not taken into account.

• Modelica Implementation
  – The waveforms of the magnetic field quantities are represented by a complex phasor:

\[ V_m(\varphi) = \text{Re}(V_m e^{-j\varphi}) = V_{m,\text{re}} \cos(\varphi) + V_{m,\text{im}} \sin(\varphi) \]

  – The specific arrangement of windings in electric machines with P pole pairs gives rise to sinusoidal dominant magnetic potential wave. The spatial period of this wave is determined by one pole pair.
Motor model

- Modelica model diagram of a permanent magnet synchronous machine
  - Electrical circuit in blue
  - Magnetic circuit in orange
  - Mechanics in grey
  - Thermal in red
- Electrical, Magnetic and Friction properties are temperature dependent
Modelica Application Libraries

- Air Conditioning
- Batteries
- Belts
- eDrives
- Engines
- FlexBody
- Fuel Cell
- Heat Exchanger
- Human Comfort
- Hydraulics
- Liquid Cooling
- Pneumatics
- Powertrain Dynamics
- Simulator
- Smart Electric Drives
- SystemID
- Terrain Server
- TIL Suite
- Vapor Cycle
- Vehicle Dynamics
- VDLMotorsports
- XMLReader
Example: Formula 1 powertrain

• Optimise the thermal management of the ERS to reduce weight and improve aerodynamic losses:
  – Intercooler sizing
  – Reduce coolant volume throughout the cooling system
• Therefore necessary to:
  – gain a better understanding of the thermal performance of the ERS devices, focussing on the ES device for this particular task
Testing environment

Open loop driver model
- Throttle
- Brake
- Steering
- Gears

Vehicle model
- Powertrain
- Chassis
- Brakes
- Tyres

World
- Coordinate system
- Gravity
- Animation settings

Atmosphere
- Pressure
- Density
- Wind speed and direction

Road model
- 3D road surface model
- Inclination
- Friction coefficient of surface
Vehicle model

• Dymola libraries:
  – Vehicle Dynamics Motorsport
    • Closed loop driver
    • Multibody chassis
    • Pacejka tyre models
    • Brakes
    • Gearbox
  – Engines
    • Power unit ICE and cooling
  – Electrical libraries
    • MGUK
    • MGUH
    • ES
Chassis model
ICE, MGU and Coolant System integration

- Parameterised mean value engine model is pressure charged by means of a mapped turbocharger and integrated with the MGUH and MGUK in the power unit model below:
**MGUs**

- **Electrical effects**
  - Internal resistance
  - Heat losses
  - Inductance
- **Magnetic effects**
  - Heat losses
  - Core losses
- **Mechanical effects:**
  - Inertia
  - Frictional losses
  - Heat rejection
  - Torque reaction into MGU support

**ES**

- **Equivalent Circuit model**
  - Internal resistance
  - Diffusion limitation
  - Thermal losses
  - Resistance, Capacitance, OCV with temperature & SOC dependency
Conclusions

- Ability to interface multiple domains to understand the whole system dynamics
- Multiple ERS control strategies were evaluated using physical system models
- Models are real-time capable using a Quasi steady state version of the motors and can be used within a driver simulator