ACTUATION 2015
D31.1 – Specification for EMA-library approach and components

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ABSTRACT The objective of this document is to specify the A2015 EMA simulation model library and to describe the modeling approach chosen.
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## 1. Glossary

<table>
<thead>
<tr>
<th>Abbreviation / acronym</th>
<th>Description</th>
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<tr>
<td>A/C</td>
<td>Aircraft</td>
</tr>
<tr>
<td>CS</td>
<td>Circular Spline</td>
</tr>
<tr>
<td>EMA</td>
<td>Electro Mechanical Actuator</td>
</tr>
<tr>
<td>EMI</td>
<td>ElectroMagnetic Interference</td>
</tr>
<tr>
<td>ESD</td>
<td>ElectroStatic Discharge</td>
</tr>
<tr>
<td>FCS</td>
<td>Flight Control System</td>
</tr>
<tr>
<td>FMI</td>
<td>Functional mock-up interface</td>
</tr>
<tr>
<td>FS</td>
<td>Flex spline</td>
</tr>
<tr>
<td>HIRF</td>
<td>High Intensity Radiated Field</td>
</tr>
<tr>
<td>HLS</td>
<td>High Lift System</td>
</tr>
<tr>
<td>LRU</td>
<td>Line Replaceable Unit</td>
</tr>
<tr>
<td>MLG</td>
<td>Main Landing Gear</td>
</tr>
<tr>
<td>M&amp;S</td>
<td>Modelling and Simulation</td>
</tr>
<tr>
<td>MSL</td>
<td>Modelica Standard Library</td>
</tr>
<tr>
<td>MTBF</td>
<td>Mean Time Between Failure</td>
</tr>
<tr>
<td>MTBUR</td>
<td>Mean Time Between Unscheduled Removals</td>
</tr>
<tr>
<td>NWS</td>
<td>Nose Wheel Steering</td>
</tr>
<tr>
<td>PDE</td>
<td>Power Drive Electronic</td>
</tr>
<tr>
<td>PFCS</td>
<td>Primary Flight Control System</td>
</tr>
<tr>
<td>4PMSM</td>
<td>Permanent Magnet Synchronous Machine</td>
</tr>
<tr>
<td>SCADE</td>
<td>Safety Critical Application Development Environment</td>
</tr>
<tr>
<td>SRM</td>
<td>Synchronous Reluctance Machine</td>
</tr>
<tr>
<td>S/W</td>
<td>Software</td>
</tr>
<tr>
<td>TBA</td>
<td>To Be Answered (by the Airframer or Supplier)</td>
</tr>
<tr>
<td>TBC</td>
<td>To Be Confirmed</td>
</tr>
<tr>
<td>TBD</td>
<td>To Be Defined</td>
</tr>
<tr>
<td>WG</td>
<td>Wave generator</td>
</tr>
</tbody>
</table>
2. Executive Summary

The objective of this document is to specify the A2015 EMA simulation model library. The focus of the library is on system simulation aspects and includes redundant components, nominal and faulty modes of operation, and transient (dynamic) and steady state conditions. Applications of this library include all development stages from the pre-design phase to virtual validation.

The scope of the library and the general modeling approach are described. The top level model components, their interfaces, parameters and failure modes are specified. The library will be implemented in the object oriented modeling language Modelica.
3. Introduction / Scope

The main objective for the EMA simulation model library is the development of a tool-independent standard for EMA libraries contributing to the establishment of a “common language” through the development process of EMAs for aerospace applications (conceptual design, specification, development, and validation) and through the supply chain.

The modeling approach is compliant with SP1 requirements and addresses specific aspects of the EMA design process not covered by existing tools. Apart from the coverage of physical effects relevant for an optimized design the EMA library contains:

- Single-click replaceable models of different scope and level of detail for the core EMA components (multi-level approach)
- Failure modes of the core EMA components
- Standardized fault injection
- Standardized implementation of thermal flows and heat exchange
- Standardized model breakdown structure with common interfaces based on existing standard library [3]
- Interoperability with established tools via the FMI standard [2]

The types of components included in the library (mechanical, electrical, thermal, sensors, etc) are listed in more detail in chapter 4. The library architecture and the implementation conventions (modeling approach, data organization, library test, example models, and library documentation) are described in chapter 5, the library structure is explained in chapter 6. In chapter 7 definitions of the library model components are given in detail (relevant physical effects, interdependencies and links with other components, failure modes, implementation levels, parameterization, model interfaces and expected numerical challenges). In the last chapter 8 a conclusion is drawn and the next steps are outlined.

Apart from this specification, three papers have been published regarding the library. Reference [15] gives an overview of the library implementation, [16] and [17] describe electric inverter and motor implementations, and [18] describes the fault triggering mechanism used.
4. Analysis of needs

The possible applications of M&S in aerospace EMA development are manifold. They include all development stages from the pre-design phase to virtual validation. The A2015 library focuses on system aspects including redundant components under nominal and faulty modes of operation in transient (dynamic) and steady state conditions.

This chapter lists specific needs, properties and goals of the library. They include:

- The library is available to all WP3 project partners.
- The library is usable by a broad audience, not only by simulation specialists. For that reason a good, elaborate documentation and a collection of typical example applications of the major component models must be included.
- The library supports redundant components and component failure injection.
- Apart from general system dynamics aspects the scope of the library includes:
  - Concept assessments (architectural design)
  - Performance assessments (functional and behavioral design)
  - Sizing (as far as system aspects are involved)
  - Component requirements definition and fail case assumptions
  - System reaction and performance in case of failures and failure transients
  - Virtual design validation
  - Environmental thermal condition assessments
  - Control and monitoring function development and validation
- The library does not include:
  - Distributed parameter models
  - Kinematics (use Modelica multibody library or the Planar Mechanics Library to be released soon by the Modelica Association)
  - Overall thermal analysis (use specialized tool)
  - Stress reports
  - Complex control, monitoring and state of health algorithms
  - Control design tools
- The library includes simulation models for the following types of components (additional utility models like communication buses, etc. are contained as well):
  - Electrical:
    1. PMSM, (salient and non-salient)
    2. SRM
    3. DC machine
    4. Power electronic inverter
  - Mechanical:
    1. Rotation to translation power transformers (no distinction will be made in the structure of models between ACME, ballscrew and rollerscrews, only parameters will differ).
    2. Rotation to Rotation power transformers:
      - Harmonic drive
      - Spur gear reducer
      - Epicyclic reducers
      - Planar gearwheels
      - Worm gear reducer
• Bevel gear reducer
• Bearing losses
• Differential gearbox
• Torque limiter

  o Sensors:
    ▪ Linear position sensor
    ▪ Force sensor
    ▪ Angular position sensor
    ▪ Torque sensor
    ▪ Current sensor
    ▪ Temperature sensor

  o Thermal components:
    ▪ Heat-sink

  o Communication buses.

  o Controllers:
    ▪ Continuous/Discrete P/PI/PD/PID
    ▪ Current controller
    ▪ Speed controller
    ▪ Position controller
    ▪ Force fight compensator

• For each type of component model the purpose, modeling levels, coverage of physical effects, failure injection capabilities, parameterization, interface definition and limitations have to be assessed. For a detailed list of this properties and the model implementations chosen see chapter 7.

• The library covers all design phases from concept assessment to virtual validation. To fulfill that need for each component several replaceable models of different scope and level of detail are implemented (multilevel approach). The following modeling levels have been agreed between partners (a color code for the icons has been defined and associated with each level):
  o level 1 (red): perfect
  o level 2 (blue): with linear effects, invertible
  o level 3 (grey): nonlinear, invertible (e.g. using tanh instead of sign functions)
  o level 4 (green): hard nonlinear effects (which trigger state events like the standard lossy gear model or discretization of states), time discrete (sampled) models
  o level 5 (dark yellow): fully switched model like an switching inverter (based on state events)

This scheme does not imply that for all components models of all levels are included or for each level only a single model is included. The modeling level scheme is introduced in order to
  o help to organize the component models
  o give the user a quick idea what kind of effects a certain model does include.

• The library components are structured and the component models are parameterized according to common component data sheets as far as applicable.

• The library is coded in Modelica, Version 3.3 (reasons include redundancy, variant and data handling). Dymola is used as development tool, but tool-specific coding shall be avoided as far as reasonable.

Outlook: Possible future library extensions include:
• Mass, volume, cost, etc. design optimization by providing specialized modeling levels while maintaining EMA model topology (see WP 3.2).
• Automated safety and reliability analysis.
5. Library architecture, conventions for library implementations

5.1. Overview

The EMA library will be implemented in the Modelica language. The implementation follows the multi-level approach, providing models with different levels of complexity for major components which share a common interface. Reasons for Modelica usage are enhanced reusability and maintainability of EMA models, ease of model configuration (substitute a simple model by a more sophisticated model of the same component), and an integrated structure for models and parameter data. The implementation follows a strictly object oriented, a causal approach. Common properties shared by several models (or parts of models) are collected in respective base classes. The same holds for parameter data, which is organized in parameter records.

An important aspect of the EMA library is the modeling of component failures. For reasons of a unified mapping of failures to models and easy handling of failure injection a dedicated failure triggering sublibrary is used, which has been provided by DLR for all involved partners.

The desired structure of the EMA library is described in more detail in chapter 6 by means of an example library.

5.2. Multi level modeling approach

Each major component has at least a very simple model representation without any failure and several enhanced model representations with reasonable failure modes. The levels of model complexity have been defined in chapter 4. For easy substitution of a simple model by an enhanced one (or vice versa) such sets of models are inherited from a common base class, containing the interfaces and any other parts common to all members of this model collection. It’s important that the interfaces of all such models of a multilevel model collection are the same because otherwise model substitution would not be possible without additional level-specific connections between submodel interfaces. The modeler is free to use inherited models with different interfaces internally, e.g. in order to reuse model parts common to several other models. If a modeling level inherently contains additional interfaces (e.g. a thermal port) it is implemented as a conditional class instance in the base class with proper defaults.

The model substitution mechanism to be used within a collection of models with different levels is replaceable / redeclare / constrained by (not conditional, parameterized instantiation). It is shared by all models of the EMA library and enriched by corresponding annotations (choicesAllMatching).

5.3. Sensor signal bus usage

Each sensor model delivers an ideal signal (mostly based on the sensor elements of the Modelica Standard Library), a status flag, and a real signal containing noise, drift, etc. or a faulty signal (if the respective failure is triggered). For easy handling of the ideal / real signals they are delivered by the sensor model via a predefined signal bus.
5.4. Data organization

The model parameter data is organized in the same way the models are organized: Common data of a certain component is collected in a base record. The different actual data sets inherit from that base record. For all parameters reasonable default values are provided.

All the data definition and data values are kept in a separate package in order to allow users to work on the same models but with different parameter data. Each user’s (private) data set inherits from the (public) data record in the EMA library data subpackage.

5.5. Library test, example models and documentation

Each major library component is implemented together with a representative test model (organized in a test model subpackage) and scripts for each major test case (reference to scripts stored in the respective model). This test model represents a kind of component model specification, implementing at least the most important specifications (there will be cases where more than a single test model is necessary). E.g. for an electric motor model a collection of test models could be provided including simulations for plotting current / torque / speed characteristics for nominal and failure operations (e.g. winding short circuit). In case a component model is changed, the test model provides a quick check for functional correctness. Ideally, looking at a collection of test models serves as a (executable) model specification, indicating the scope of a model and providing a test bench for the case of modifying the model.

For the higher level library components example models are provided (going to an own top level subpackage) illustrating the typical usage of them and providing a baseline for checking simulation results of new library versions. The collection of example models provides a jump start in using the library. They also serve as a starting point for a comparison of simulation results with measured data, if applicable.

All the library and model documentation is contained in the library in HTML format as Modelica annotation (Info layer). The library main package and all major subpackages have a dedicated info class (model classes which contain only documentation but no equations, no icons and no other models), containing the relevant library and component documentation along with a user’s guide or tutorial. This holds also for the examples subpackage and its single classes. The Modelica Standard Library serves as a guideline for library and model documentation.

5.6. Library conventions

Following common standards within a model library makes its usage easier. Therefore the EMA library implementation follows standard conventions for naming and structuring. They are described in more detail in [1]. Some additional conventions are explained in the following paragraphs.

Groups of generic classes (e.g. interface definitions, type definitions, basic blocks with fixed causality, etc.) are collected in dedicated subpackages. The structure of the MSL provides a good guideline on how to group models in packages and subpackages. Chapter 6 gives an additional best practice example.

All model classes in the final library version are organized in a top level Modelica package within a single file (during library development it’s much more convenient to store model classes and packages in different files). In contrast to that all data records and packages with collections of data are stored in dedicated files for each single record and dedicated directories for each package. Thus all library model code is kept together while maintaining full flexibility of parameterization and parameter data storage. If
a new version of the library is delivered, the user must exchange a common single file only without interference with his private parameter data or private models.

Failure injection is done using a dedicated failure injection library (additional top-level package) which is provided by DLR to all partners [18].
6. Content description / library structure

The content and structure of the library is described below according to an early pre-release (0.1.5). The Failure Injection Lib is a separate package (see [18]).

In the package browser of a Modelica tool the library structure can be examined: Apart from the major model component categories (Mechanical, Electrical, Controllers, Sensors) there are User's Guide and Examples packages, collections of more generic model components (Interfaces), common library utilities and parameter data packages. If appropriate, the major component categories are substructured (e.g. Mechanical: Rotational, Translational, Planar). Some subpackages have own interface definitions (e.g. Mechanics.Rotational.Interfaces) and an own sensor model subpackage.

As a general guideline model classes are rearranged in appropriate subpackages if “too many” of them (say 10) are contained in a single package, or if they belong to completely different categories (e.g. partial classes and baseclasses which are not used directly are contained in an own subpackage).

How to define components:

- Follow the principle of “single source of information” for every part of a model and every parameter.
- Structure that information in base classes and inherit from them accordingly. This holds also for data records.
- Please always keep in mind to keep things as simple as possible (but not simpler, of course ...). Complexity of good Modelica models mostly originates from a combination of many simple model components, not from a few complex model components.
7. Components Definition

In this chapter the major library model components are defined. The definition follows the scheme outlined in the “Component Requirements Template”. As described in chapter 4 for each of these components a model with minimal functionality without failures and at least one model with enhanced functionality and reasonable failure modes is implemented.

Detailed library documentation is given as HTML code in annotations of the respective models in Modelica based on the documentation below. Since parameterization and interface definition is extracted automatically from the Modelica code by Dymola, it is not documented separately in the model.

7.1. Motors

7.1.1. Permanent Magnet Synchronous Machine (salient and non-salient)

- Engineering needs and relevant physical effects to be modeled
  
  Basic function
  
  Torque generation:
  
  • Field torque in case of non-salient motor;
  • Field and reluctance torque in case of salient motor.

  Thermal pre-design
  
  Copper, iron and mechanical losses.

  Thermal model.

  Advanced physical effects
  
  Magnetic saturation.

  Torque ripple.

  Fault conditions analyzed
  
  Three phase short circuit fault.

  Three phase open circuit fault.

  Single phase short circuit fault.

  Single phase open circuit fault.

- Interdependencies and links with other components:

  Electrical side
  
  Models are provided by plugs as electrical interface, and they can be fed through the following components:

  • three phase sources (voltage or current);
  • current controller, which gives as output $abc$ voltages;
  • power electronic inverter.

  Mechanical side
  
  Models can even operate without connecting any mechanical components (e.g. inertia), to the rotor shaft (flange).
Failure modes and their relevance

- Three phase short circuit fault: mandatory
- Three phase open circuit fault: mandatory
- Single phase short circuit fault: optional
- Single phase open circuit fault: optional

Implementation levels and main model attributes

**Basic**
- Torque generation exploiting the electrical torque constant.
- Basic losses (copper and mechanical). Losses calculation is optional according to the model user needs.
- Thermal model. Its use is optional according to the model user needs.
- Torque ripple generation. Its use is optional according to the model user needs.

**Standard**
- Modeling according the equivalent circuit in the $dq$ rotating reference frame.
- Field and reluctance torque generation.
- Advanced losses (copper, iron and mechanical). Iron and mechanical losses calculation is optional according to the model user needs.
- Thermal model. Its use is optional according to the model user needs.
- Torque ripple generation. Its use is optional according to the model user needs.

**Saturation**
- Modeling according the equivalent circuit in the $dq$ rotating reference frame.
- Field and reluctance torque generation.
- Magnetic saturation effect. Its implementation is optional according to the model user needs.
- Advanced losses (copper, iron and mechanical). Iron and mechanical losses calculation is optional according to the model user needs.
- Thermal model. Its use is optional according to the model user needs.
- Torque ripple generation. Its use is optional according to the model user needs.

**Fault**
- Field and reluctance torque generation.
- Single and three phase faults.
- Advanced losses (copper, iron and mechanical). Iron and mechanical losses calculation is optional according to the model user needs.
- Thermal model. Its use is optional according to the model user needs.
- Torque ripple generation. Its use is optional according to the model user needs.
Parameterization

**Basic:** (number of phases is implicitly considered equal to 3 and the stator windings are star connected with floating neutral point)

*General parameters*
- **Pole pairs number**
  - Value can be read directly from motor rated plate. If not specified, then default value is used.
- **Rotor's moment of inertia**
  - Value set by the model user. If not specified, then default value is used.
- **Stator's moment of inertia**
  - Value set by the model user. If not specified, then default value is used. This parameter is required, when mechanical support is adopted.
- **Electrical torque constant**
  - Value set by the model user. If not specified, then default value is used.
- **Maximum current**
  - Value set by the model user. If not specified, then default value is used. When the actual current is higher than the typed value, the simulation will be stopped and a warning message will provided.
- **Maximum torque**
  - Value set by the model user. If not specified, then default value is used. When the actual current is higher than the typed value, the simulation will be stopped and a warning message will provided.
- **Maximum speed**
  - Value set by the model user. If not specified, then default value is used. When the actual current is higher than the typed value, the simulation will be stopped and a warning message will provided.

*Losses parameters:*
- **Line-to-neutral resistance**
  - Value can be read directly from motor rated plate. If not specified, then default value is used. This parameter is required, when the losses calculation is enabled.
- **Resistance reference temperature**
  - Value set by the model user. If not specified, then default value is used. This parameter is required, when thermal model is adopted.
- **Linear temperature coefficient**
  - Value can be chosen from a drop list menu or typed by the model user according to the winding material. If not specified, then default value is used. This parameter is required, when thermal model is adopted.
- **Friction coefficient**
  - Value set by the model user. If not specified, then default value is used. This parameter is required, when the losses calculation is enabled.
### Thermal model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor mass</td>
<td>Value used to calculate the equivalent heat capacity of the thermal model. If not specified, then default value is used. This parameter is required, when the thermal model is enabled.</td>
</tr>
<tr>
<td>Equivalent specific heat capacity</td>
<td>Value can be chosen from a drop list menu or typed by the model user according to the ratio between copper and iron. If not specified, then default value is used. This parameter is required, when the thermal model is enabled. It is used to compute the equivalent heat capacity of the thermal model.</td>
</tr>
<tr>
<td>Heat transfer coefficient</td>
<td>Value used to calculate the equivalent thermal conductance of the thermal model, assuming the heat is transferred by convection. If not specified, then default value is used. This parameter is required, when the thermal model is enabled.</td>
</tr>
<tr>
<td>Motor convection area</td>
<td>Value used to calculate the equivalent thermal conductance of the thermal model, assuming the heat is transferred by convection. If not specified, then default value is used. This parameter is required, when the thermal model is enabled.</td>
</tr>
</tbody>
</table>

### Torque ripple parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque ripple amplitude</td>
<td>Value set by the model user. If not specified, then default value is used. This parameter is required, when the torque ripple generation is enabled.</td>
</tr>
<tr>
<td>Machine rated frequency</td>
<td>Value can be obtained from the machine rated speed. If not specified, then default value is used. This parameter is required, when the torque ripple generation is enabled.</td>
</tr>
<tr>
<td>Torque ripple frequency</td>
<td>Value set by the model user. If not specified, then default value is used. This parameter is required, when the torque ripple generation is enabled.</td>
</tr>
</tbody>
</table>

**Standard:** (number of phase is implicitly considered equal to 3 and the stator windings are star connected with floating neutral point)

### General parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole pairs number</td>
<td>Value can be read directly from motor rated plate. If not specified, then default value is used.</td>
</tr>
<tr>
<td>Rotor's moment of inertia</td>
<td>Value set by the model user. If not specified, then default value is used.</td>
</tr>
<tr>
<td>Stator's moment of inertia</td>
<td>Value set by the model user. If not specified, then default value is used. This parameter is required, when mechanical support is adopted.</td>
</tr>
</tbody>
</table>
Maximum current | Value set by the model user. If not specified, then default value is used. When the actual current is higher than the typed value, the simulation will be stopped and a warning message will provided.

Maximum torque | Value set by the model user. If not specified, then default value is used. When the actual current is higher than the typed value, the simulation will be stopped and a warning message will provided.

Line-to-neutral resistance | Value can be read directly from motor rated plate. If not specified, then default value is used. When the actual current is higher than the typed value, the simulation will be stopped and a warning message will provided.

Resistance reference temperature | Value set by the model user. If not specified, then default value is used. This parameter is required, when thermal model is adopted.

Linear temperature coefficient | Value can be chosen from a drop list menu or typed by the model user according to the winding material. If not specified, then default value is used. This parameter is required, when thermal model is adopted.

d-axis inductance | Value can be read from motor datasheet. If not specified, then default value is used.

q-axis inductance | Value can be read from motor datasheet. If not specified, then default value is used.

Back electromotive force | Value used to compute the permanent magnet flux. If not specified, then default value is used.

Machine rated frequency | Value used to compute the permanent magnet flux. If not specified, then default value is used.

**Losses parameters:**

Specific iron losses | Value can be read from magnetic material datasheet. Model provides a drop list menu, from where magnetic materials, commonly used in electrical machines' construction, can be selected. This parameter is required, when the losses calculation is enabled.

Magnetic material mass | Value referred to the stator mass and used to calculated the iron losses. If not specified, then default value is used. This parameter is required, when the losses calculation is enabled.

Friction coefficient | Value set by the model user. If not specified, then default value is used. This parameter is required, when the losses calculation is enabled.

**Thermal model parameters**

Same parameters as reported in the “Thermal model parameters” section of the “Basic” model.
Torque ripple parameters

Same parameters as reported in the “Torque ripple parameters” section of the “Basic” model.

Saturation: (number of phase is implicitly considered equal to 3 and the stator windings are star connected with floating neutral point)

General parameters

Pole pairs number Value can be read directly from motor rated plate. If not specified, then default value is used.

Rotor’s moment of inertia Value set by the model user. If not specified, then default value is used.

Stator’s moment of inertia Value set by the model user. If not specified, then default value is used. This parameter is required, when mechanical support is adopted.

Maximum current Value set by the model user. If not specified, then default value is used. When the actual current is higher than the typed value, the simulation will be stopped and a warning message will provided.

Maximum torque Value set by the model user. If not specified, then default value is used. When the actual current is higher than the typed value, the simulation will be stopped and a warning message will provided.

Line-to-neutral resistance Value can be read directly from motor rated plate If not specified, then default value is used.

Resistance reference temperature Value set by the model user. If not specified, then default value is used. This parameter is required, when thermal model is adopted.

Linear temperature coefficient Value can be chosen from a drop list menu or typed by the model user according to the winding material. If not specified, then default value is used. This parameter is required, when thermal model is adopted.

No saturated d-axis inductance Value can be read from motor datasheet. If not specified, then default value is used. This parameter is neglected, when magnetic saturation effect is considered.

No saturated q-axis inductance Value can be read from motor datasheet. If not specified, then default value is used. This parameter is neglected, when magnetic saturation effect is considered.

Back electromotive force Value used to compute the permanent magnet flux. If not specified, then default value is used.

Machine rated frequency Value used to compute the permanent magnet flux. If not specified, then default value is used.
Saturation parameters

d-axis inductance curve: This curve shows the d-axis inductance trend as a function of the d-axis current. Model is already provided with a d-axis inductance curve obtained from finite element simulations. At the same time, model gives the opportunity to load a curve provided by the model user. This parameter is required when magnetic saturation effect is considered.

q-axis inductance curve: This curve shows the q-axis inductance trend as a function of the q-axis current. Model is already provided with a d-axis inductance curve obtained from finite element simulations. At the same time, model gives the opportunity to load a curve provided by the model user. This parameter is required when magnetic saturation effect is considered.

Permanent magnet flux curve: This curve shows the permanent magnet flux as a function of the q-axis current. Model is already provided with this curve obtained from finite element simulations. At the same time, model gives the opportunity to load a curve provided by the model user. This parameter is required when magnetic saturation effect is considered.

Losses parameters:

Same parameters as reported in the “Losses parameters” section of the “Standard” model.

Thermal model parameters

Same parameters as reported in the “Thermal model parameters” section of the “Basic” model.

Torque ripple parameters

Same parameters as reported in the “Torque ripple parameters” section of the “Basic” model.

Fault: (number of phase is implicitly considered equal to 3 and the stator windings are star connected with floating neutral point)

General parameters

Same parameters as reported in the “General parameters” section of the “Standard” model.

Losses parameters:

Same parameters as reported in the “Losses parameters” section of the “Standard” model.

Thermal model parameters

Same parameters as reported in the “Thermal model parameters” section of the “Basic” model.

Torque ripple parameters

Same parameters as reported in the “Torque ripple parameters” section of the “Basic” model.
Model interfaces and respective attached components

**Electrical side:**
- Three phase plugs (positive and negative) Stator windings supply using phase quantities (voltage and current). Plugs can be connected to AC sources, current controller or power electronic inverter.

**Mechanical side:**
- Mechanical flange Rotor shaft. Flange can be connected to mechanical source (such as torque, speed and position) and/or mechanical components (e.g. inertia).
- Mechanical support Housing support. It can be connected to mechanical source (such as torque, speed and position) and/or mechanical components (e.g. inertia).

**Thermal model:**
- Heat port It can be connected to the motor cooling system.

**Expected numerical challenges**
- When thermal model and torque ripple are simultaneously used the simulation becomes slow. According to the controllers bandwidth, the ripple torque could be filtered off.

### 7.1.2. Synchronous Reluctance Machine (SRM)

**Engineering needs and relevant physical effects to be modeled**
- Basic function Reluctance torque generation.
- Thermal pre-design Copper, iron and mechanical losses. Thermal model.
- Advanced physical effects Magnetic saturation. Torque ripple.

**Interdependencies and links with other components:**
- Electrical side Models are provided by plugs as electrical interface, and they can be fed through the following components:
  - three phase sources (voltage or current);
  - current controller, which gives as output abc voltages;
  - power electronic inverter.
- Mechanical side Models can even operate without connecting any mechanical components (e.g. inertia), to the rotor shaft (flange).
• Implementation levels and main model attributes

Standard: Modeling according the equivalent circuit in the dq rotating reference frame.
Field and reluctance torque generation.
Advanced losses (copper, iron and mechanical). Iron and mechanical losses calculation is optional according to the model user needs.
Thermal model. Its use is optional according to the model user needs.
Torque ripple generation. Its use is optional according to the model user needs.

Saturation: Modeling according the equivalent circuit in the dq rotating reference frame.
Field and reluctance torque generation.
Magnetic saturation effect. Its implementation is optional according to the model user needs.
Advanced losses (copper, iron and mechanical). Iron and mechanical losses calculation is optional according to the model user needs.
Thermal model. Its use is optional according to the model user needs.
Torque ripple generation. Its use is optional according to the model user needs.

• Parameterization

Standard: (number of phase is implicitly considered equal to 3 and the stator windings are star connected with floating neutral point)

General parameters

Pole pairs number: Value can be read directly from motor rated plate. If not specified, then default value is used.
Rotor's moment of inertia: Value set by the model user. If not specified, then default value is used.
Stator's moment of inertia: Value set by the model user. If not specified, then default value is used. This parameter is required, when mechanical support is adopted.
Maximum current: Value set by the model user. If not specified, then default value is used. When the actual current is higher than the typed value, the simulation will be stopped and a warning message will provided.
Maximum torque: Value set by the model user. If not specified, then default value is used. When the actual current is higher than the typed value, the simulation will be stopped and a warning message will provided.
Maximum speed: Value set by the model user. If not specified, then default value is used. When the actual current is higher than the typed value, the simulation will be stopped and a warning message will provided.
Line-to-neutral resistance: Value can be read directly from motor rated plate If not specified, then default value is used.
## Resistance reference temperature
Value set by the model user. If not specified, then default value is used. This parameter is required, when thermal model is adopted.

## Linear temperature coefficient
Value can be chosen from a drop list menu or typed by the model user according to the winding material. If not specified, then default value is used. This parameter is required, when thermal model is adopted.

## d-axis inductance
Value can be read from motor datasheet. If not specified, then default value is used.

## q-axis inductance
Value can be read from motor datasheet. If not specified, then default value is used.

## Losses parameters:

### Specific iron losses
Value can be read from magnetic material datasheet. Model provides a drop list menu, from where magnetic materials, commonly used in electrical machines’ construction, can be selected. This parameter is required, when the losses calculation is enabled.

### Magnetic material mass
Value referred to the stator mass and used to calculated the iron losses. If not specified, then default value is used. This parameter is required, when the losses calculation is enabled.

### Rated current
Value can be read directly from motor rated plate. If not specified, then default value is used.

### Friction coefficient
Value set by the model user. If not specified, then default value is used. This parameter is required, when the losses calculation is enabled.

## Thermal model parameters

### Motor mass
Value used to calculate the equivalent heat capacity of the thermal model. If not specified, then default value is used. This parameter is required, when the thermal model is enabled.

### Equivalent specific heat capacity
Value can be chosen from a drop list menu or typed by the model user according to the ration between copper and iron. If not specified, then default value is used. This parameter is required, when the thermal model is enabled. It is used to compute the equivalent heat capacity of the thermal model.

### Heat transfer coefficient
Value used to calculate the equivalent thermal conductance of the thermal model, assuming the heat is transferred by convection. If not specified, then default value is used. This parameter is required, when the thermal model is enabled.

### Motor convection area
Value used to calculate the equivalent thermal conductance of the thermal model, assuming the heat is transferred by convection. If not specified, then default value is used. This parameter is required, when the thermal model is enabled.

## Torque ripple parameters
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque ripple amplitude</td>
<td>Value set by the model user. If not specified, then default value is used. This parameter is required, when the torque ripple generation is enabled.</td>
</tr>
<tr>
<td>Machine rated frequency</td>
<td>Value can be obtained from the machine rated speed. If not specified, then default value is used. This parameter is required, when the torque ripple generation is enabled.</td>
</tr>
<tr>
<td>Torque ripple frequency</td>
<td>Value set by the model user. If not specified, then default value is used. This parameter is required, when the torque ripple generation is enabled.</td>
</tr>
<tr>
<td>Saturation</td>
<td>(number of phase is implicitly considered equal to 3 and the stator windings are star connected with floating neutral point)</td>
</tr>
<tr>
<td>General parameters</td>
<td></td>
</tr>
<tr>
<td>Pole pairs number</td>
<td>Value can be read directly from motor rated plate. If not specified, then default value is used.</td>
</tr>
<tr>
<td>Rotor's moment of inertia</td>
<td>Value set by the model user. If not specified, then default value is used.</td>
</tr>
<tr>
<td>Stator's moment of inertia</td>
<td>Value set by the model user. If not specified, then default value is used. This parameter is required, when mechanical support is adopted.</td>
</tr>
<tr>
<td>Maximum current</td>
<td>Value set by the model user. If not specified, then default value is used. When the actual current is higher than the typed value, the simulation will be stopped and a warning message will provided.</td>
</tr>
<tr>
<td>Maximum torque</td>
<td>Value set by the model user. If not specified, then default value is used. When the actual current is higher than the typed value, the simulation will be stopped and a warning message will provided.</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>Value set by the model user. If not specified, then default value is used. When the actual current is higher than the typed value, the simulation will be stopped and a warning message will provided.</td>
</tr>
<tr>
<td>Line-to-neutral resistance</td>
<td>Value can be read directly from motor rated plate. If not specified, then default value is used.</td>
</tr>
<tr>
<td>Resistance reference temperature</td>
<td>Value set by the model user. If not specified, then default value is used. This parameter is required, when thermal model is adopted.</td>
</tr>
</tbody>
</table>
Linear temperature coefficient: Value can be chosen from a drop list menu or typed by the model user according to the winding material. If not specified, then default value is used. This parameter is required, when thermal model is adopted.

No saturated d-axis inductance: Value can be read from motor datasheet. If not specified, then default value is used. This parameter is neglected, when magnetic saturation effect is considered.

No saturated q-axis inductance: Value can be read from motor datasheet. If not specified, then default value is used. This parameter is neglected, when magnetic saturation effect is considered.

Saturation parameters:
- d-axis inductance curve: This curve shown the d-axis inductance trend as function of the d-axis current. Model is already provided with a d-axis inductance curve obtained from finite element simulations. At the same time, model gives the opportunity to load a curve provided by the model user. This parameter is required, when magnetic saturation effect is considered.
- q-axis inductance curve: This curve shown the q-axis inductance trend as function of the q-axis current. Model is already provided with a d-axis inductance curve obtained from finite element simulations. At the same time, model gives the opportunity to load a curve provided by the model user. This parameter is required, when magnetic saturation effect is considered.

Losses parameters:
- Same parameters as reported in the “Losses parameters” section of the “Standard” model.

Thermal model parameters:
- Same parameters as reported in the “Thermal model parameters” section of the “Standard” model.

Torque ripple parameters:
- Same parameters as reported in the “Torque ripple parameters” section of the “Standard” model.

Model interfaces and respective attached components:

Electrical side:
- Three phase plugs (positive and negative): Stator windings supply using phase quantities (voltage and current). Plugs can be connected to AC sources, current controller or power electronic inverter.

Mechanical side:
- Mechanical flange: Rotor shaft. Flange can be connected to mechanical source (such as torque, speed and position) and/or mechanical components (e.g. inertia).
Mechanical support: Housing support. It can be connected to mechanical source (such as torque, speed and position) and/or mechanical components (e.g. inertia).

Thermal model:
Heat port: It can be connected to the motor cooling system.

- Expected numerical challenges
  When thermal model and torque ripple are simultaneously used the simulation becomes slow. According to the controllers bandwidth, the ripple torque could be filtered off.

### 7.1.3. Direct Current Machine

- Engineering needs and relevant physical effects to be modeled
  - Basic function: Magnetic flux and torque generation.
  - Thermal pre-design:
    - Copper in the armature circuit;
    - Copper losses in the field circuit;
    - Iron losses;
    - Mechanical losses;
    - Brushes losses;
    - Thermal model.
  - Advanced physical effects: Magnetic saturation.

- Interdependencies and links with other components:
  - Electrical side: without attached DC voltage sources (for supplying armature and field circuits) model cannot be operated DC.
  - Mechanical side: Models can even operate without connecting any mechanical components (e.g. inertia), to the rotor shaft (flange).

- Implementation levels and main model attributes
  - Standard: Magnetic flux and torque generation.
    - Advanced losses (copper, iron brushes, and mechanical). Iron, brushes and mechanical losses calculation is optional according to the model user needs.
    - Thermal model. Its use is optional according to the model user needs.
    - Torque ripple generation. Its use is optional according to the model user needs.
  - Saturation: Magnetic flux and torque generation.
    - Advanced losses (copper, iron brushes, and mechanical). Iron, brushes and mechanical losses calculation is optional according to the model user needs.
    - Magnetic saturation effect. Its implementation is optional according to the model user needs.
Thermal model. Its use is optional according to the model user needs.
Torque ripple generation. Its use is optional according to the model user needs.

- Parameterization

**Standard:** (DC machine with independent excitation)

**General parameters**

- **Number of poles**
  Value can be read directly from motor rated plate. If not specified, then default value is used.

- **Rotor's moment of inertia**
  Value set by the model user. If not specified, then default value is used.

- **Stator's moment of inertia**
  Value set by the model user. If not specified, then default value is used. This parameter is required, when mechanical support is adopted.

- **Rated power**
  Value can be read directly from motor rated plate. If not specified, then default value is used.

- **Rated speed**
  Value can be read directly from motor rated plate. If not specified, then default value is used.

- **Maximum torque**
  Value set by the model user. If not specified, then default value is used. When the actual current is higher than the typed value, the simulation will be stopped and a warning message will be provided.

- **Maximum speed**
  Value set by the model user. If not specified, then default value is used. When the actual current is higher than the typed value, the simulation will be stopped and a warning message will be provided.

**Armature circuit parameters**

- **Rated voltage**
  Value can be read directly from motor rated plate. If not specified, then default value is used.

- **Rated current**
  Value can be read directly from motor rated plate. If not specified, then default value is used.

- **Maximum current**
  Value set by the model user. If not specified, then default value is used. When the actual current is higher than the typed value, the simulation will be stopped and a warning message will be provided.

- **Resistance**
  Value can be read directly from motor datasheet. If not specified, then default value is used.

- **Resistance reference temperature**
  Value set by the model user. If not specified, then default value is used. This parameter is required, when thermal model is adopted.
### Linear temperature coefficient
Value can be chosen from a drop list menu or typed by the model user according to the winding material. If not specified, then default value is used. This parameter is required, when thermal model is adopted.

### Inductance
Value can be read from motor datasheet. If not specified, then default value is used.

### Field circuit parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage</td>
<td>Value can be read directly from motor rated plate. If not specified, then default value is used.</td>
</tr>
<tr>
<td>Rated current</td>
<td>Value can be read directly from motor rated plate. If not specified, then default value is used.</td>
</tr>
<tr>
<td>Maximum current</td>
<td>Value set by the model user. If not specified, then default value is used. When the actual current is higher than the typed value, the simulation will be stopped and a warning message will provided.</td>
</tr>
<tr>
<td>Resistance</td>
<td>Value can be read directly from motor datasheet. If not specified, then default value is used.</td>
</tr>
<tr>
<td>Resistance reference temperature</td>
<td>Value set by the model user. If not specified, then default value is used. This parameter is required, when thermal model is adopted.</td>
</tr>
<tr>
<td>Linear temperature coefficient</td>
<td>Value can be chosen from a drop list menu or typed by the model user according to the winding material. If not specified, then default value is used. This parameter is required, when thermal model is adopted.</td>
</tr>
<tr>
<td>Inductance</td>
<td>Value can be read from motor datasheet. If not specified, then default value is used.</td>
</tr>
</tbody>
</table>

### Losses parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pairs of brushes</td>
<td>Value can be read from motor datasheet. If not specified, then default value is used. This parameter is required, when the losses calculation is enabled.</td>
</tr>
<tr>
<td>Brushes voltage drop</td>
<td>Value can be read from brush datasheet and it depends by the brush material. This parameter refers to the voltage drop across a pair of brushes. Model provides a drop list menu, from where brush materials, commonly used in DC machines, can be selected. This parameter is required, when the losses calculation is enabled.</td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>Value set by the model user. If not specified, then default value is used. This parameter is required, when the losses calculation is enabled.</td>
</tr>
</tbody>
</table>
**Thermal model parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor mass</td>
<td>Value used to calculate the equivalent heat capacity of the thermal model. If not specified, then default value is used. This parameter is required, when the thermal model is enabled.</td>
</tr>
<tr>
<td>Equivalent specific heat capacity</td>
<td>Value can be chosen from a drop list menu or typed by the model user according to the ration between copper and iron. If not specified, then default value is used. This parameter is required, when the thermal model is enabled. It is used to compute the equivalent heat capacity of the thermal model.</td>
</tr>
<tr>
<td>Heat transfer coefficient</td>
<td>Value used to calculate the equivalent thermal conductance of the thermal model, assuming the heat is transferred by convection. If not specified, then default value is used. This parameter is required, when the thermal model is enabled.</td>
</tr>
<tr>
<td>Motor convection area</td>
<td>Value used to calculate the equivalent thermal conductance of the thermal model, assuming the heat is transferred by convection. If not specified, then default value is used. This parameter is required, when the thermal model is enabled.</td>
</tr>
</tbody>
</table>

**Torque ripple parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque ripple amplitude</td>
<td>Value set by the model user. If not specified, then default value is used. This parameter is required, when the torque ripple generation is enabled.</td>
</tr>
<tr>
<td>Machine rated frequency</td>
<td>Value can be obtained from the machine rated speed. If not specified, then default value is used. This parameter is required, when the torque ripple generation is enabled.</td>
</tr>
<tr>
<td>Torque ripple frequency</td>
<td>Value set by the model user. If not specified, then default value is used. This parameter is required, when the torque ripple generation is enabled.</td>
</tr>
</tbody>
</table>

**Saturation: (DC machine with independent excitation)**

| General parameters                     | Same parameters as reported in the “General parameters” section of the “Standard” model. |
| Armature circuit parameters            | Same parameters as reported in the “Armature circuit parameters” section of the “Standard” model. |
| Field circuit parameters               | Same parameters as reported in the “Field circuit parameters” section of the “Standard” model. |
| Saturation parameters                  | Field current value at the knee of the current Vs flux curve. Value set by the model user. If not specified, then default value is used. This parameter is required, when magnetic saturation effect is considered. |
| Field current at slight saturation    | Field flux value at the knee of the current Vs flux curve. Value set by the model user. If not specified, then default value is used. This parameter is required, when magnetic saturation effect is considered. |
Field flux at deep saturation

Field flux value at the end of the current Vs flux curve. Value set by the model user. If not specified, then default value is used. This parameter is required, when magnetic saturation effect is considered.

Lostes parameters:

Same parameters as reported in the “Losses parameters” section of the “Standard” model.

Thermal model parameters

Same parameters as reported in the “Thermal model parameters” section of the “Standard” model.

Torque ripple parameters

Same parameters as reported in the “Torque ripple parameters” section of the “Standard” model.

- Model interfaces and respective attached components

Electrical side:

Armature positive and negative pins

Armature circuit terminals. Pins can be connected to DC voltage source.

Field positive and negative pins

Field circuit terminals. Pins can be connected to DC voltage source.

Mechanical side:

Mechanical flange

Rotor shaft. Flange can be connected to mechanical source (such as torque, speed and position) and/or mechanical components (e.g. inertia).

Mechanical support

Housing support. It can be connected to mechanical source (such as torque, speed and position) and/or mechanical components (e.g. inertia).

Thermal model:

Heat port

It can be connected to the motor cooling system.

- Expected numerical challenges

When thermal model and torque ripple are simultaneously used the simulation becomes slow. According to the controllers bandwidth, the ripple torque could be filtered off.
7.2. Power Drive Electronics

7.2.1. Power Electronic Inverter

- Engineering needs and relevant physical effects to be modeled
  Basic function: Generation of demanded control signals
  Transformation between DC and AC
  Thermal pre-design: Power losses
  Fault/Redundancy Analysis: Open/Short Circuit Faults
  Harmonic Analysis: Switching

- Interdependencies and links with other components:
  DC supply: without attached DC supply the inverter model cannot be operated
  Current controller: without three phase inputs from an attached current controller the model cannot be operated
  Heat Sink: If the Heat Port within the model is enabled it is recommended that a Heat Sink Model is used connected to the Heat Port in order to give an accurate representation of the thermal response.

- Failure modes and their relevance
  Single and Multi-Phase Short Circuits: mandatory
  Single and Multi-Phase Open Circuits: mandatory

- Implementation levels and main model attributes
  No Losses: No Switching, No losses
  Linear Losses: No Switching, Basic consideration of losses with simple parameterisation and thermal response
  Non Linear Losses: No Switching, More accurate consideration of losses with more complex parameterisation if high accuracy required.
  Current Based Losses: No Switching, Highest losses accuracy; based on current through the device. Parameterisation requires device curves from data sheets.
  Fault: No Switching, Ability to introduce basic Multi-Phase fault
  Switching: Switching, Single and Multi-Phase faults, Basic Losses

- Parameterization

  Non-Switching:
  Linear Losses: Inverter Efficiency. User defined constant efficiency. Default value is also given.
  Non Linear Losses: Inverter Efficiency and Rated Power, User defined efficiency curve, defined per unit against specified rated power. Default values are also given.
  Current Based Losses: Switching Frequency and Resistance of Switch when conducting (constant values, user defined but with default values). Also Switching Energy Loss and Device
Voltage Drop Collector to Emitter (user defined curves but with default values).

Switching:
Inverter Rated Power Default value given, accuracy of losses within model is dependent on the accuracy of this value.

Thermal:
Thermal Resistance IGBT Junction to Case Value can be read directly from IGBT module data sheets. If no user specified value is given then default value is used.
Time Constant IGBT Junction to Case Value can be read directly from IGBT module data sheets. If no user specified value is given then default value is used.
Thermal Resistance IGBT to Heat Sink Value can be read directly from IGBT module data sheets. If no user specified value is given then default value is used.

• Failure injection:
Non-Switching: Boolean: 0 = normal operation, 1 = fault.
Fault Options available: Three Phase
Switching: Integer: 0 = normal operation, 1 = short circuit, 2 = open circuit.
Fault Options available: Switch 1, Switch 2, Switch 3, Switch 4, Switch 5, Switch 6, Phase A, Phase B, Phase C and Three Phase

• Model interfaces and respective attached components
Inputs:
DC Electrical DC Supply (Positive and Negative Pins)
Control Signals Three Phase Real Numbers
Output:
AC Electrical Three Phase Plug for Load / Electrical Machine
Thermal Heat Port Inverter Losses in the form of Heat

• Expected numerical challenges
Switching model much more numerically demanding that Non-Switching models. Faults may result in large numerical peaks due to ideal switching or large current values in the case of short circuit.
7.3. PowerSources

Basic package for power sources. It consists of a single power source and has a partial interface model to extend from to guarantee the replaceability in case of user added models.

All models have the following set of parameters:

DC voltage of source \( v_{\text{supply}} \)

7.4. Mechanical Parts

7.4.1. Screw Drives

- Engineering needs and relevant physical effects to be modeled

<table>
<thead>
<tr>
<th>Needs</th>
<th>Functional</th>
<th>Power sizing</th>
<th>Thermal balance</th>
<th>Natural dynamics</th>
<th>Closed loop performance (dynamics / accuracy)</th>
<th>Consumed energy</th>
<th>Geometrical integration (mass/envelope)</th>
<th>Response to failure</th>
<th>Load propagation</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical effects</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Lead (perfect power transformer)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
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</tr>
<tr>
<td>Stroke</td>
<td>Y</td>
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<td></td>
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</tr>
<tr>
<td>Mass and inertia (screw and nut)</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>Y</td>
<td>P</td>
<td>Y</td>
</tr>
<tr>
<td>Heat capacitance (screw and nut)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compliance (including backlash or lost motion)</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>Y</td>
<td>P</td>
<td>Y</td>
</tr>
<tr>
<td>Friction (including load, speed, temp effects)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>P</td>
<td>Y</td>
</tr>
<tr>
<td>Length and diameter</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Means to consider them</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td>P</td>
<td>P</td>
<td>Y</td>
<td>P</td>
<td>Y</td>
</tr>
<tr>
<td>Quadriport mechanical</td>
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<tr>
<td>Thermal port</td>
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</tbody>
</table>

- Interdependencies and links with other components:
  - Housing: translational and/or rotational mechanical ports (plus heat port if merged)
  - Driving shaft (from gear or motor): rotational mechanical port (plus translational mechanical port in quadriport implementation)
  - Load: translational mechanical port (plus rotational mechanical port in quadriport implementation)
  - Ambiant: Heat port

- Failure modes and their relevance
  - Normal mode: normal frictional losses and normal backlash (or preload) Mandatory
  - Jammed mode: increased frictional losses Mandatory
  - Free mode: increased backlash or reduced preload Mandatory
• Implementation levels and main model attributes
  
  Inertia preferably implemented outside the nutscrew models using MSL models.
  
  1) Basic
    Perfect power transformation plus travel limit (out-of-range warning), offset in R/T motion
  
  2) Linear, continuous
    Viscous friction loss in effort path, linear compliance with parallel damping in position path
  
  3) Non linear, continuous
    Speed/load/temperature dependent friction, backlash/preloading/lost motion implemented as continuous functions at order 0 at least (friction vs. speed and force vs. position are continuous functions). \textit{Regular} model without Influence of preload on friction, \textit{advanced} model with temperature effects implemented by tabulated friction parameters vs. temperature.
  
  4) Non linear, discontinuous
    Speed/load/temperature dependent friction, backlash/preloading/lost motion. \textit{Regular} model without influence of preload on friction, \textit{advanced} model with influence of preload on friction. All models implemented with rigorous state event handling.
  
  5) Non linear, switched
    Not applicable as far as local effects not addressed (e.g. teeth engagement)

  Levels 2 to 4 have failure injections for jamming and free run.

• Parameterization

  \textit{Perfect transformation}: pitch, travel, offset in RT position transformation
  
  a) Friction:
    • for level 2, viscous friction coefficient
    • for levels 3 and 4, including dependency to load, velocity and temperature. First set as parameterized equations with tabulated friction parameters depending on temperature. Possibly second set as 3D tables (friction parameters vs. velocity and temperature).
  
  b) Backlash/preloading/lost motion:
    • For level 2, linear stiffness and associated linear viscous damping
    • For models 3 and 4 as parameterized equations. Possibly in a second step as tables of force vs relative position.

  Initial conditions
  Excepted inertia, state variables for compliance effects.
  Initial states for level 4 models

Failure injection parameters
• Boolean for failed jammed
• Boolean for failed free
• Possibly real to enable modeling progressive degradation

Parameter record according to modeling level
As far as possible, incremental from level 1

• Model interfaces and respective attached components
  
  o Mechanical / rotational \quad \text{Drive shaft}
  
  o Mechanical / translational \quad \text{Load}
7.4.2. Harmonic Drive

- Engineering needs and relevant physical effects to be modeled

Harmonic drives are high-ratio and high-torque compact transmission systems. They provide high efficiency, near-zero backlash, and back drivability [10]. In the field of electromechanical actuation for aircraft flight control systems, harmonic drives can be used in rotary actuation applications to transform the fast and low-torque rotation of an electric motor into a slow and high-torque rotation of an output lever. Due to their near-zero backlash capabilities, they are a promising solution to minimize the risk of flutter in a control surface.

A harmonic drive is composed of three concentric elements:

1. The Circular Spline (CS) is a solid cylindrical ring with internal gear teeth

2. The Flexspline (FS) is a non-rigid, thin cylindrical cup with external teeth at the open end of the cup. The closed end of the cup is provided with a flange connection to following machine elements.

3. The Wave Generator (WG) comprises a thin-raced ball bearing fitted onto an elliptical plug, serving as a high efficiency torque converter.

![Figure 2: Harmonic Drive](image)

The Flexspline is slightly smaller in diameter than the circular spline and usually has two fewer teeth than the CS. The elliptical shape of the Wave Generator causes the teeth of the FS to engage the CS at two regions at opposite ends of the major axis of the ellipse. As the WG (input)...
rotates, the zone of tooth engagement travels with the major axis of the ellipse. For each half clockwise turn of the WG, the FS (output) moves counterclockwise by one tooth relative to the CS (fixed). Each complete clockwise rotation of the WG results in the FS moving counterclockwise by two teeth from its previous position relative to the CS [9].

**Physical Characteristics and Effects**

a. Kinematics

As for every other type of reducer, the prime characteristic of a harmonic drive is the technique it employs for upstream torque reduction. This one is not a function of the relative sizes of the toothed components, as is the case for spur gears or planetary gears, but simply of the number of teeth. The standard or catalogue reduction ratio of a harmonic drive is characterized by:

\[ t_3 = \frac{n_{fs} - n_{cs}}{n_{fs}} \]

where \( n_{fs} \) and \( n_{cs} \) correspond to the number of teeth of the flex spline and the circular spline respectively. Furthermore, the reduction ratio depends on the driving arrangement chosen for a particular application [11]:

1. **Circular Spline – Fixed**
   Wave Generator – Input
   Flex Spline – Output

   \[ t_3 = \frac{t_3 - 1}{1} \]

2. **Flex Spline – Fixed**
   Wave Generator – Input
   Circular Spline – Output

   \[ t_3 = \frac{t_3 + 1}{1} \]

3. **Wave Generator – Fixed**
   Flex Spline – Input
   Circular Spline – Output

   \[ t_3 = \frac{t_3 + 1}{1} \]

b. Torque Balance

The torque balance equations of the harmonic drive model are reflected to the input of the device. The inertia is lumped to a total inertia term \( J \) as means of minimizing the number of required parameters. Figure 2 shows the model of the Harmonic Drive schematically. Although this type of gearbox is characterized for having near to zero backlash, the property is included in the model for the sake of flexibility.
The corresponding torque balance equation is:

\[ J \cdot \omega_a = T_p + \frac{1}{i^2} \left( c \cdot \left( \frac{1}{i^2} \cdot \varphi_a - \varphi_b \right) + d \cdot \left( \frac{1}{i^2} \cdot \omega_a - \omega_b \right) + T_{fr} \right) \]

This model requires two mechanical rotational interfaces at each side in order to transmit mechanical power. A structural support and a heat port are also provided. These two are selectable in order to give the user the choice to simulate respective structural or thermal effects on demand.

c. Compliance
Compliance is modeled together with structural damping and backlash. For all linear models it is modeled using the compliance coefficient \( c \) and structural damping \( d \). The values used for these two properties must be those relative to the low-speed side of the device. For nonlinear and switching models backlash is introduced and thus compliance becomes nonlinear. The backlash introduced in the model amounts to an angle \( \varphi_{bl} \) with respect to the low-speed side of the harmonic drive.

d. Frictional and Thermal losses
All losses are inherited from the “Parallel Axis Spur Gears Reducer” model. These are used as replaceable models in the harmonic drive. The user can switch between different types of losses depending on the desired level of detail.

- Interdependencies and links with other components:
  a. The model can be connected to an input external inertia at both ports if no inertias are selected in the model.
  b. All losses are linked to those of the model “GearReducer” since it is used inside the Harmonic Drive model as replaceable.

- Failure modes
  - Jamming
  - Disconnect

- Implementation levels and main model attributes

  - **Basic**: functional model
    i. Kinematics
    ii. Inertia (selectable)
    iii. Torque transmission
**Linear**: linear elastic behaviour and losses

i. Kinematics

ii. Inertia (selectable)

iii. Torque transmission

iv. Compliance

v. Linear friction (switchable)

vi. Heat transfer (selectable)

vii. Failure modes

**Nonlinear**: nonlinear elastic behaviour and losses

i. Kinematics

ii. Inertia (selectable)

iii. Torque transmission

iv. Nonlinear compliance (backlash)

v. Nonlinear friction (switchable)

vi. Heat transfer (selectable)

vii. Failure modes

- **Parameterization**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Use and remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD Inertia</td>
<td>Lumped inertia of Harmonic Drive at low-speed port</td>
</tr>
<tr>
<td>HD Mass</td>
<td>Total mass of Harmonic Drive</td>
</tr>
<tr>
<td>Reduction ratio</td>
<td>Overall reduction ratio (as given in HD Catalogue)</td>
</tr>
<tr>
<td>Compliance</td>
<td>Lumped compliance of Harmonic Drive at low-speed port</td>
</tr>
<tr>
<td>Structural damping</td>
<td>Lumped structural damping of Harmonic Drive at low-speed port</td>
</tr>
<tr>
<td>Backlash</td>
<td>Overall backlash at low-speed port</td>
</tr>
<tr>
<td>Frictional parameters</td>
<td>See section 7.4.3</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>Temperature around the device</td>
</tr>
</tbody>
</table>

  *Initial conditions*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Use and remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative initial rotation angle</td>
<td>0 deg</td>
</tr>
<tr>
<td>Relative initial rotation speed</td>
<td>0 deg/s</td>
</tr>
</tbody>
</table>
Parameter records according to modeling level:

<table>
<thead>
<tr>
<th>Modeling Level</th>
<th>Parameters</th>
</tr>
</thead>
</table>
| Basic          | Reduction ratio \( i \) [-]  
|                | Inertia \( J \) [kg·m\(^2\)] (selectable) |
| Linear         | Basic + …  
|                | Compliance \( c \) [N·m/rad]  
|                | Structural damping \( d \) [Nm·s/rad]  
|                | Linear friction parameters (see section 7.4.3)  
|                | Mass \( m \) [kg] (selectable)  
|                | Ambient Temperature \( T_a \) [°C] |
| Nonlinear      | Linear + …  
|                | Backlash angle \( \phi_{bl} \) [deg]  
|                | Nonlinear friction parameters (see section 7.4.3) |

- Model interfaces and respective attached components
  a. Drive unit (e.g. electric motor) at high-speed input side
  b. Rotary transmission device (e.g. drive lever or shaft) connected to low-speed output side
  c. Flange-type mechanical support
  d. Heat sink connected to thermal port

7.4.3. Parallel axis spur gear reducer

- Engineering needs and relevant physical effects to be modeled
  Basic function Mechanical power transmission.
  Structural pre-design Metallic material library used as source of material structural properties.
  Advanced physical effects Direct efficiency.
                        Reverse efficiency.
                        Breakout and running tare losses.
                        Load independent drag torque.
                        Speed dependent drag torque.
  Fault conditions analyzed Bearing seizure.
                        Lubricant contamination.
                        Wear.
                        Plastic deformation.
                        Ductile fracture.

- Interdependencies and links with other components:
  Models can be arranged in series with themselves composing a multistage reducer, linked to external inertias, torques and speed sources.
• Failure modes and their relevance
  Bearing seizure                     mandatory
  Plastic deformation               optional
  Wear                               mandatory
  Ductile fracture                 mandatory
  Lubricant contamination          optional

• Implementation levels and main model attributes
  LEVEL 1                          Perfect power transformation without losses, torque and speed are modified according the speed ratio. If the wheels inertias are to be considered, the dynamic equilibrium equation is calculated.
  LEVEL 2                          The output torque of the driven side is now reduced by the speed losses due to the wheels windage. If the wheels inertias are to be considered, the dynamic equilibrium equation is calculated.
  LEVEL 3                          This level also considers the static friction torque acting on the shafts and calculates its sign and value using the hyperbolic tangent approach. If the wheels inertias are to be considered the dynamic equilibrium equation is calculated.
  LEVEL 4                          The level 4 model is capable of reproducing the stuck condition whenever the driving torque is incapable of maintaining the reducer rotation. It also considers the temperature variation of efficiencies and loss parameters.

• Parameterization

  LEVEL 1:  
  General parameters
  \( z_a \)
  Number of teeth of the pinion. The value has to be set by the user.
  \( z_b \)
  Number of teeth of the gear. The value has to be set by the user.
  internalGear
  Tick box which enables the user to consider internal geared wheels; it’s used to establish the sign of the speed ratio. By default it’s deselected, denoting externally geared wheels.

  LEVEL 2:  
  General parameters
  \( z_a \)
  Number of teeth of the pinion. The value has to be set by the user.
  \( z_b \)
  Number of teeth of the gear. The value has to be set by the user.
  internalGear
  Tick box which enables the user to consider internal geared wheels; it’s used to establish the sign of the speed ratio. By default it’s deselected, denoting externally geared wheels.
linearLosses Checkbox which enables the linear losses calculations.

d_1 Linear speed loss coefficient. The value has to be set by the user who is guided by the spreadsheets.

d_2 Quadratic speed loss coefficient.

LEVEL 3:
General parameters

z_a Number of teeth of the pinion. The value has to be set by the user.

z_b Number of teeth of the gear. The value has to be set by the user.

internalGear Tick box which enables the user to consider internal geared wheels; it’s used to establish the sign of the speed ratio. By default it’s deselected, denoting externally geared wheels.

linearLosses Checkbox which enables the linear losses calculations.

d_1 Linear speed loss coefficient. The value has to be set by the user who is guided by the spreadsheets.

d_2 Quadratic speed loss coefficient.

η_mf1 Direct efficiency. The value has to be set by the user who is guided by the spreadsheets.

η_mf2 Reverse efficiency. The value has to be set by the user who is guided by the spreadsheets.

ω_0 Breakout speed. The value has to be set by the user who is guided by the spreadsheets.

τ_{BF1} Speed and load independent friction torque, A flange driving. The value has to be set by the user who is guided by the spreadsheets.

Lossygear Checkbox which enables the use of two different speed and load independent friction toques in relation to which flange (A or B) is driving.

τ_{BF2} Speed and load independent friction torque, B flange driving.

LEVEL 4:
General parameters

z_a Number of teeth of the pinion. The value has to be set by the user.

z_b Number of teeth of the gear. The value has to be set by the user.

internalGear Tick box which enables the user to consider internal geared wheels; it’s used to establish the sign of the speed ratio. By default it’s deselected, denoting externally geared wheels.

linearLosses Checkbox which enables the linear losses calculations.

d_1 Linear speed loss coefficient. The value has to be set by the user who is guided by the spreadsheets.

d_2 Quadratic speed loss coefficient.

η_mf1 Direct efficiency. The value has to be set by the user who is guided by the spreadsheets.

η_mf2 Reverse efficiency. The value has to be set by the user who is guided by the spreadsheets.
Breakout speed. The value has to be set by the user who is guided by the spreadsheets.

\( \tau_{BF1} \)  
Speed and load independent friction torque, A flange driving. The value has to be set by the user who is guided by the spreadsheets.

\( \tau_{BF2} \)  
Speed and load independent friction torque, B flange driving.

**Temperature**  
Indicates the nominal operating temperature of the reducer.

**modulus**  
Specifies the value of the pitch diameter/teeth ratio of the wheel.

**useTemperature**  
Checkbox which enables the use of temperature dependent friction factors

\( K_{f0} \)  
Represent the efficiency loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.

\( K_{s0} \)  
Represent the speed loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.

\( K_{t0} \)  
Represent the tare loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.

\( x_{\text{max}} \)  
Matrix of polynomial coefficients used to correlate the variation of: \( K_{f0} \), \( K_{s0} \), \( K_{t0} \). This matrix represent the maximum increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.

\( x_{\text{mean}} \)  
Matrix of polynomial coefficients used to correlate the variation of: \( K_{f0} \), \( K_{s0} \), \( K_{t0} \). This matrix represent the mean increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.

\( x_{\text{min}} \)  
Matrix of polynomial coefficients used to correlate the variation of: \( K_{f0} \), \( K_{s0} \), \( K_{t0} \). This matrix represent the minimum increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.

**Curves**  
Is a parameter which allows the user to select from the three type of increase factors which one is to select to perform the calculations.

**Model interfaces and respective attached components**

**Mechanical:**

- **flange_a**  
  Modelica standard flange in the rotational part of the mechanics interface library.

- **flange_b**  
  Modelica standard flange in the rotational part of the mechanics interface library.

- **support**  
  The support is used, when commanded by the user, to calculate the reaction torque necessary to maintain the reducer’s housing equilibrium.

**Thermal:**

- **Heat port**  
  It can be connected to other component to propagate the heat flux, untimely, to the housing.
7.4.4. Epicyclic gear reducer type 1

This reducer is a planetary gear box consisting of an inner sun wheel, an outer Planet Carrier wheel and one or more planet wheels located between sun and ring wheel.

- Engineering needs and relevant physical effects to be modeled
  Basic function Mechanical power transmission.
  Structural pre-design Metallic material library used as source of material structural properties.
  Advanced physical effects Direct efficiency.
    Reverse efficiency.
    Breakout and running tare losses.
    Load independent drag torque.
    Speed dependent drag torque.
  Fault conditions analyzed Bearing seizure.
    Lubricant contamination.
    Wear.
    Plastic deformation.
    Ductile fracture.

- Interdependencies and links with other components:
  Models can be arranged in series with themselves composing a multistage reducer, linked to external inertias, torques and speed sources.

- Failure modes and their relevance
  Bearing seizure mandatory
  Plastic deformation optional
  Wear mandatory
  Ductile fracture mandatory
  Lubricant contamination optional

- Implementation levels and main model attributes
  LEVEL 1 Perfect power transformation without losses, torque and speed are modified according the speed ratio. If the wheels inertias are to be considered, the dynamic equilibrium equation is calculated.
  LEVEL 2 The output torque of the driven side is now reduced by the speed losses due to the wheels windage. If the wheels inertias are to be considered, the dynamic equilibrium equation is calculated.
  LEVEL 3 This level also considers the static friction torque acting on the shafts and calculates its sign and value using the hyperbolic tangent approach. If the wheels inertias are to be considered the dynamic equilibrium equation is calculated.
  LEVEL 4 The level 4 model is capable of reproducing the stuck condition whenever the driving torque is incapable of maintaining the reducer rotation. It also considers the
temperature variation of efficiencies and loss parameters.

- Parameterization

**LEVEL 1:**

*General parameters*

- \( z_1 \): Number of teeth of the input gear. The value has to be set by the user.
- \( z_2 \): Number of teeth of the ring gear. The value has to be set by the user.
- \( z_3 \): Number of teeth of the planet gear. The value has to be set by the user.
- \( N_p \): Number of planets. The value has to be set by the user who is guided by the spreadsheets.

**LEVEL 2:**

*General parameters*

- \( z_1 \): Number of teeth of the input gear. The value has to be set by the user.
- \( z_2 \): Number of teeth of the ring gear. The value has to be set by the user.
- \( z_3 \): Number of teeth of the planet gear. The value has to be set by the user.
- \( N_p \): Number of planets. The value has to be set by the user who is guided by the spreadsheets.
- \( \text{linearLosses} \): Checkbox which enables the linear losses calculations.
- \( d_1 \): Linear speed loss coefficient. The value has to be set by the user who is guided by the spreadsheets.
- \( d_2 \): Quadratic speed loss coefficient.

**LEVEL 3:**

*General parameters*

- \( z_1 \): Number of teeth of the input gear. The value has to be set by the user.
- \( z_2 \): Number of teeth of the ring gear. The value has to be set by the user.
- \( z_3 \): Number of teeth of the planet gear. The value has to be set by the user.
- \( N_p \): Number of planets. The value has to be set by the user who is guided by the spreadsheets.
- \( \text{linearLosses} \): Checkbox which enables the linear losses calculations.
- \( d_1 \): Linear speed loss coefficient. The value has to be set by the user who is guided by the spreadsheets.
- \( d_2 \): Quadratic speed loss coefficient.
- \( \eta_{mf1} \): Direct efficiency. The value has to be set by the user who is guided by the spreadsheets.
- \( \eta_{mf2} \): Reverse efficiency. The value has to be set by the user who is guided by the spreadsheets.
- \( \omega_0 \): Breakout speed. The value has to be set by the user who is guided by the spreadsheets.
LEVEL 4:

**General parameters**

- $z_1$: Number of teeth of the input gear. The value has to be set by the user.
- $z_2$: Number of teeth of the ring gear. The value has to be set by the user.
- $z_3$: Number of teeth of the planet gear. The value has to be set by the user.
- $N_p$: Number of planets. The value has to be set by the user who is guided by the spreadsheets.

**Other parameters**

- $\tau_{BF1}$: Speed and load independent friction torque, A flange driving. The value has to be set by the user who is guided by the spreadsheets.
- $\tau_{BF2}$: Speed and load independent friction torque, B flange driving.
- Lossygear: Checkbox which enables the use of two different speed and load independent friction torques in relation to which flange (A or B) is driving.

**Temperature**

Indicates the nominal operating temperature of the reducer.

**Column vector of the wheels diameters.**

**Checkbox which enables the use of temperature dependent friction factors.**

$K_{f0}$: Represent the efficiency loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.

$K_{s0}$: Represent the speed loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.

$K_{t0}$: Represent the tare loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.

$X_{max}$: Matrix of polynomial coefficients used to correlate the variation of: $K_{f0}$, $K_{s0}$, $K_{t0}$. This matrix represent the maximum increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.
Matrix of polynomial coefficients used to correlate the variation of: $K_{f_0}$, $K_{s_0}$, $K_{t_0}$. This matrix represent the mean increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.

Matrix of polynomial coefficients used to correlate the variation of: $K_{f_0}$, $K_{s_0}$, $K_{t_0}$. This matrix represent the minimum increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.

Is a parameter which allows the user to select from the three type of increase factors which one is to select to perform the calculations.

- Model interfaces and respective attached components
  - Mechanical:
    - flange_a: Modelica standard flange in the rotational part of the mechanics interface library.
    - flange_b: Modelica standard flange in the rotational part of the mechanics interface library.
    - support: The support is used, when commanded by the user, to calculate the reaction torque necessary to maintain the reducer’s housing equilibrium.

  - Thermal:
    Heat port can be connected to other components to propagate the heat flux.

### 7.4.5. Epicyclic gear reducer type 2

This type of epicyclical reducer is comprised of a planet carrier which constitute the input shaft of the reducer, several doubly geared planets, connected to the carrier via rolling elements, a fixed gear and the output solar.

- Engineering needs and relevant physical effects to be modeled
  - Basic function: Mechanical power transmission.
  - Structural pre-design: Metallic material library used as source of material structural properties.

- Interdependencies and links with other components:
Models can be arranged in series with themselves composing a multistage reducer, linked to external inertias, torques and speed sources.

- **Failure modes and their relevance**
  - Bearing seizure: mandatory
  - Plastic deformation: optional
  - Wear: mandatory
  - Ductile fracture: mandatory
  - Lubricant contamination: optional

- **Implementation levels and main model attributes**
  - **LEVEL 1**: Perfect power transformation without losses. Torque and speed are modified according to the speed ratio. If the wheels inertias are to be considered, the dynamic equilibrium equation is calculated.
  - **LEVEL 2**: The output torque of the driven side is now reduced by the speed losses due to the wheels windage. If the wheels inertias are to be considered, the dynamic equilibrium equation is calculated.
  - **LEVEL 3**: This level also considers the static friction torque acting on the shafts and calculates its sign and value using the hyperbolic tangent approach. If the wheels inertias are to be considered the dynamic equilibrium equation is calculated.
  - **LEVEL 4**: The level 4 model is capable of reproducing the stuck condition whenever the driving torque is incapable of maintaining the reducer rotation. It also considers the temperature variation of efficiencies and loss parameters.

- **Parameterization**

  **LEVEL 1:**
  - General parameters
    - $z_1$: Number of teeth of the output gear. The value has to be set by the user.
    - $z_2$: Number of teeth of the fixed gear. The value has to be set by the user.
    - $z_3$: Number of teeth of the planet gear meshing with the output gear. The value has to be set by the user.
    - $z_4$: Number of teeth of the planet gear meshing with the fixed gear. The value has to be set by the user.

  **LEVEL 2:**
  - General parameters
    - $z_1$: Number of teeth of the output gear. The value has to be set by the user.
    - $z_2$: Number of teeth of the fixed gear. The value has to be set by the user.
    - $z_3$: Number of teeth of the planet gear meshing with the output gear. The value has to be set by the user.
    - $z_4$: Number of teeth of the planet gear meshing with the fixed gear. The value has to be set by the user.
linearLosses

Checkbox which enables the linear losses calculations.

$d_1$

Linear speed loss coefficient. The value has to be set by the user who is guided by the spreadsheets.

$d_2$

Quadratic speed loss coefficient.

LEVEL 3:

General parameters

$z_1$

Number of teeth of the output gear. The value has to be set by the user.

$z_2$

Number of teeth of the fixed gear. The value has to be set by the user.

$z_3$

Number of teeth of the planet gear meshing with the output gear. The value has to be set by the user.

$z_4$

Number of teeth of the planet gear meshing with the fixed gear. The value has to be set by the user.

linearLosses

Checkbox which enables the linear losses calculations.

$d_1$

Linear speed loss coefficient. The value has to be set by the user who is guided by the spreadsheets.

$d_2$

Quadratic speed loss coefficient.

$\eta_{mf1}$

Direct efficiency. The value has to be set by the user who is guided by the spreadsheets.

$\eta_{mf2}$

Reverse efficiency. The value has to be set by the user who is guided by the spreadsheets.

$\omega_0$

Breakout speed. The value has to be set by the user who is guided by the spreadsheets.

$\tau_{BF1}$

Speed and load independent friction torque, A flange driving. The value has to be set by the user who is guided by the spreadsheets.

Lossygear

Checkbox which enables the use of two different speed and load independent friction toques in relation to which flange (A or B) is driving.

$\tau_{BF2}$

Speed and load independent friction torque, B flange driving.

LEVEL 4:

General parameters

$z_1$

Number of teeth of the output gear. The value has to be set by the user.

$z_2$

Number of teeth of the fixed gear. The value has to be set by the user.

$z_3$

Number of teeth of the planet gear meshing with the output gear. The value has to be set by the user.

$z_4$

Number of teeth of the planet gear meshing with the fixed gear. The value has to be set by the user.

linearLosses

Checkbox which enables the linear losses calculations.

$d_1$

Linear speed loss coefficient. The value has to be set by the user who is guided by the spreadsheets.

$d_2$

Quadratic speed loss coefficient.

$\eta_{mf1}$

Direct efficiency. The value has to be set by the user who is guided by the spreadsheets.

$\eta_{mf2}$

Reverse efficiency. The value has to be set by the user who is guided by the spreadsheets.
\( \omega_0 \) Breakout speed. The value has to be set by the user who is guided by the spreadsheets.

\( \tau_{BF1} \) Speed and load independent friction torque, A flange driving. The value has to be set by the user who is guided by the spreadsheets.

\( \tau_{BF2} \) Speed and load independent friction torque, B flange driving.

diameter Column vector of the wheels diameters.

\( N_p \) Number of planets composing the reducer.

Temperature Indicates the nominal operating temperature of the reducer.

useTemperature Checkbox which enables the use of temperature dependent friction factors

\( Kf_0 \) Represent the efficiency loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.

\( Ks_0 \) Represent the speed loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.

\( Kt_0 \) Represent the tare loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.

\( x_{max} \) Matrix of polynomial coefficients used to correlate the variation of: \( Kf_0, Ks_0, Kt_0 \). This matrix represent the maximum increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.

\( x_{mean} \) Matrix of polynomial coefficients used to correlate the variation of: \( Kf_0, Ks_0, Kt_0 \). This matrix represent the mean increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.

\( x_{min} \) Matrix of polynomial coefficients used to correlate the variation of: \( Kf_0, Ks_0, Kt_0 \). This matrix represent the minimum increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.

Curves Is a parameter which allows the user to select from the three type of increase factors which one is to select to perform the calculations.

- Model interfaces and respective attached components

  Mechanical:
  - flange_a Modelica standard flange in the rotational part of the mechanics interface library.
  - flange_b Modelica standard flange in the rotational part of the mechanics interface library.
  - support The support is used, when commanded by the user, to calculate the reaction torque necessary to maintain the reducer's housing equilibrium.
Thermal:
Heat port can be connected to other component to propagate the heat flux.

7.4.6. Geared Rotary Actuator Type I

This compound planetary gearset contains a sun gear receiving the input torque, a ring gear providing the output torque, two stationary ring gears symmetrically placed at the two sides of the output ring gear, multiple planet gears meshing with the sun gears. Each planet gear consists of three pinions: the outer end pinion gears are identical, as are the two fixed outer ring gears.

- Engineering needs and relevant physical effects to be modeled
  Basic function Mechanical power transmission.
  Structural pre-design Metallic material library used as source of material structural properties.
  Advanced physical effects Direct efficiency.
  Advanced physical effects Reverse efficiency.
  Advanced physical effects Breakout and running tare losses.
  Advanced physical effects Load independent drag torque.
  Advanced physical effects Speed dependent drag torque.
  Fault conditions analyzed Bearing seizure.
  Fault conditions analyzed Lubricant contamination.
  Fault conditions analyzed Wear.
  Fault conditions analyzed Plastic deformation.
  Fault conditions analyzed Ductile fracture.

- Interdependencies and links with other components:
  Models can be arranged in series with themselves composing a multistage reducer, linked to external inertias, torques and speed sources.

- Failure modes and their relevance
  Bearing seizure mandatory
  Plastic deformation optional
  Wear mandatory
  Ductile fracture mandatory
  Lubricant contamination optional

- Implementation levels and main model attributes
  LEVEL 1 Perfect power transformation without losses, torque and speed are modified according the speed ratio. If the wheels inertias are to be considered, the dynamic equilibrium equation is calculated.
  LEVEL 2 The output torque of the driven side is now reduced by the speed losses due to the wheels windage. If the wheels inertias are to be considered, the dynamic equilibrium equation is calculated.
  LEVEL 3 This level also considers the static friction torque acting on the shafts and calculates its sign and value using the hyperbolic tangent approach. If the wheels inertias are to be considered the dynamic equilibrium equation is calculated.
LEVEL 4

The level 4 model is capable of reproducing the stuck condition whenever the driving torque is incapable of maintaining the reducer rotation. It also considers the temperature variation of efficiencies and loss parameters.

- Parameterization

**LEVEL 1:**

*General parameters*

- $z_1$: Number of teeth of the input gear. The value has to be set by the user who is guided by the spreadsheets.
- $z_2$: Number of teeth of the lateral gears in the planets. The value has to be set by the user who is guided by the spreadsheets.
- $z_3$: Number of teeth of the central gear in the planets. The value has to be set by the user who is guided by the spreadsheets.
- $z_4$: Number of teeth of the output gear. The value has to be set by the user who is guided by the spreadsheets.
- $z_5$: Number of teeth of the two fixed gears. The value has to be set by the user who is guided by the spreadsheets.

**LEVEL 2:**

*General parameters*

- $z_1$: Number of teeth of the input gear. The value has to be set by the user who is guided by the spreadsheets.
- $z_2$: Number of teeth of the lateral gears in the planets. The value has to be set by the user who is guided by the spreadsheets.
- $z_3$: Number of teeth of the central gear in the planets. The value has to be set by the user who is guided by the spreadsheets.
- $z_4$: Number of teeth of the output gear. The value has to be set by the user who is guided by the spreadsheets.
- $z_5$: Number of teeth of the two fixed gears. The value has to be set by the user who is guided by the spreadsheets.

**linearLosses**: Checkbox which enables the linear losses calculations.

- $d_1$: Linear speed loss coefficient. The value has to be set by the user who is guided by the spreadsheets.
- $d_2$: Quadratic speed loss coefficient.

**LEVEL 3:**

*General parameters*

- $z_1$: Number of teeth of the input gear. The value has to be set by the user who is guided by the spreadsheets.
- $z_2$: Number of teeth of the lateral gears in the planets. The value has to be set by the user who is guided by the spreadsheets.
- $z_3$: Number of teeth of the central gear in the planets. The value has to be set by the user who is guided by the spreadsheets.
### LEVEL 4:

#### General parameters

- **$z_1$**: Number of teeth of the input gear. The value has to be set by the user who is guided by the spreadsheets.
- **$z_2$**: Number of teeth of the lateral gears in the planets. The value has to be set by the user who is guided by the spreadsheets.
- **$z_3$**: Number of teeth of the central gear in the planets. The value has to be set by the user who is guided by the spreadsheets.
- **$z_4$**: Number of teeth of the output gear. The value has to be set by the user who is guided by the spreadsheets.
- **$z_5$**: Number of teeth of the two fixed gears. The value has to be set by the user who is guided by the spreadsheets.
- **linearLosses**: Checkbox which enables the linear losses calculations.
- **$d_1$**: Linear speed loss coefficient. The value has to be set by the user who is guided by the spreadsheets.
- **$d_2$**: Quadratic speed loss coefficient.
- **$\eta_{mf1}$**: Direct efficiency. The value has to be set by the user who is guided by the spreadsheets.
- **$\eta_{mf2}$**: Reverse efficiency. The value has to be set by the user who is guided by the spreadsheets.
- **$\omega_0$**: Breakout speed. The value has to be set by the user who is guided by the spreadsheets.
- **$T_{BF1}$**: Speed and load independent friction torque, A flange driving. The value has to be set by the user who is guided by the spreadsheets.
- **LossyGear**: Checkbox which enables the use of two different speed and load independent friction torques in relation to which flange (A or B) is driving.
- **$T_{BF2}$**: Speed and load independent friction torque, B flange driving.
diameter  Column vector of the wheels diameters.
Np  Number of planets composing the reducer.
Temperature  Indicates the nominal operating temperature of the reducer.
useTemperature  Checkbox which enables the use of temperature dependent friction factors
Kf₀  Represent the efficiency loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.
Ks₀  Represent the speed loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.
Kt₀  Represent the tare loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.
x_{max}  Matrix of polynomial coefficients used to correlate the variation of: Kf₀, Ks₀, Kt₀. This matrix represent the maximum increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.
x_{mean}  Matrix of polynomial coefficients used to correlate the variation of: Kf₀, Ks₀, Kt₀. This matrix represent the mean increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.
x_{min}  Matrix of polynomial coefficients used to correlate the variation of: Kf₀, Ks₀, Kt₀. This matrix represent the minimum increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.
Curves  Is a parameter which allows the user to select from the three type of increase factors which one is to select to perform the calculations.

- Model interfaces and respective attached components

**Mechanical:**
- flange_a  Modelica standard flange in the rotational part of the mechanics interface library.
- flange_b  Modelica standard flange in the rotational part of the mechanics interface library.
- support  The support is used, when commanded by the user, to calculate the reaction torque necessary to maintain the reducer’s housing equilibrium.

**Thermal:**
Heat port can be connected to other component to propagate the heat flux.

### 7.4.7. Geared Rotary Actuator Type II

This compound planetary gearset contains a sun gear receiving the input torque, a ring gear providing the output torque, one stationary ring providing the reaction torque, multiple planet gears meshing with the sun gears.
• Engineering needs and relevant physical effects to be modeled
  Basic function Mechanical power transmission.
  Structural pre-design Metallic material library used as source of material structural properties.
  Advanced physical effects Direct efficiency.
  Breakout and running tare losses.
  Load independent drag torque.
  Speed dependent drag torque.
  Fault conditions analyzed Bearing seizure.
  Lubricant contamination.
  Wear.
  Plastic deformation.
  Ductile fracture.

• Interdependencies and links with other components:
  Models can be arranged in series with themselves composing a multistage reducer, linked to external inertias, torques and speed sources.

• Failure modes and their relevance
  Bearing seizure mandatory
  Plastic deformation optional
  Wear mandatory
  Ductile fracture mandatory
  Lubricant contamination optional

• Implementation levels and main model attributes
  LEVEL 1 Perfect power transformation without losses, torque and speed are modified according the speed ratio. If the wheels inertias are to be considered, the dynamic equilibrium equation is calculated.
  LEVEL 2 The output torque of the driven side is now reduced by the speed losses due to the wheels windage. If the wheels inertias are to be considered, the dynamic equilibrium equation is calculated.
  LEVEL 3 This level also considers the static friction torque acting on the shafts and calculates its sign and value using the hyperbolic tangent approach. If the wheels inertias are to be considered the dynamic equilibrium equation is calculated.
  LEVEL 4 The level 4 model is capable of reproducing the stuck condition whenever the driving torque is incapable of maintaining the reducer rotation. It also considers the temperature variation of efficiencies and loss parameters.

• Parameterization

  LEVEL 1:
  General parameters
**LEVEL 2:**

**General parameters**

- \( z_1 \): Number of teeth of the gear 1. The value has to be set by the user who is guided by the spreadsheets.
- \( z_2 \): Number of teeth of the gear 2. The value has to be set by the user who is guided by the spreadsheets.
- \( z_3 \): Number of teeth of the gear 3. The value has to be set by the user who is guided by the spreadsheets.
- \( z_4 \): Number of teeth of the gear 4. The value has to be set by the user who is guided by the spreadsheets.
- \( z_5 \): Number of teeth of the gear 5. The value has to be set by the user who is guided by the spreadsheets.
- \( z_6 \): Number of teeth of the gear 6. The value has to be set by the user who is guided by the spreadsheets.
- \( z_7 \): Number of teeth of the gear 7. The value has to be set by the user who is guided by the spreadsheets.
- \( z_8 \): Number of teeth of the gear 8. The value has to be set by the user who is guided by the spreadsheets.
- \( z_9 \): Number of teeth of the gear 9. The value has to be set by the user who is guided by the spreadsheets.

**LEVEL 3:**

**General parameters**

- \( z_1 \): Number of teeth of the gear 1. The value has to be set by the user who is guided by the spreadsheets.
- \( z_2 \): Number of teeth of the gear 2. The value has to be set by the user who is guided by the spreadsheets.
- \( z_3 \): Number of teeth of the gear 3. The value has to be set by the user who is guided by the spreadsheets.
- \( z_4 \): Number of teeth of the gear 4. The value has to be set by the user who is guided by the spreadsheets.
Number of teeth of the gear 5. The value has to be set by the user who is guided by the spreadsheets.

Number of teeth of the gear 6. The value has to be set by the user who is guided by the spreadsheets.

Number of teeth of the gear 7. The value has to be set by the user who is guided by the spreadsheets.

Number of teeth of the gear 8. The value has to be set by the user who is guided by the spreadsheets.

Number of teeth of the gear 9. The value has to be set by the user who is guided by the spreadsheets.

Checkbox which enables the linear losses calculations.

Linear speed loss coefficient. The value has to be set by the user who is guided by the spreadsheets.

Quadratic speed loss coefficient.

Direct efficiency. The value has to be set by the user who is guided by the spreadsheets.

Reverse efficiency. The value has to be set by the user who is guided by the spreadsheets.

Breakout speed. The value has to be set by the user who is guided by the spreadsheets.

Speed and load independent friction torque, A flange driving. The value has to be set by the user who is guided by the spreadsheets.

Checkbox which enables the use of two different speed and load independent friction torques in relation to which flange (A or B) is driving.

Speed and load independent friction torque, B flange driving.

**LEVEL 4:**

**General parameters**

Number of teeth of the gear 1. The value has to be set by the user who is guided by the spreadsheets.

Number of teeth of the gear 2. The value has to be set by the user who is guided by the spreadsheets.

Number of teeth of the gear 3. The value has to be set by the user who is guided by the spreadsheets.

Number of teeth of the gear 4. The value has to be set by the user who is guided by the spreadsheets.

Number of teeth of the gear 5. The value has to be set by the user who is guided by the spreadsheets.

Number of teeth of the gear 6. The value has to be set by the user who is guided by the spreadsheets.

Number of teeth of the gear 7. The value has to be set by the user who is guided by the spreadsheets.

Number of teeth of the gear 8. The value has to be set by the user who is guided by the spreadsheets.

Number of teeth of the gear 9. The value has to be set by the user who is guided by the spreadsheets.

Checkbox which enables the linear losses calculations.

Linear speed loss coefficient. The value has to be set by the user who is guided by the spreadsheets.

Quadratic speed loss coefficient.
\( \eta_{mf1} \) Direct efficiency. The value has to be set by the user who is guided by the spreadsheets.

\( \eta_{mf2} \) Reverse efficiency. The value has to be set by the user who is guided by the spreadsheets.

\( \omega_0 \) Breakout speed. The value has to be set by the user who is guided by the spreadsheets.

\( \tau_{BF1} \) Speed and load independent friction torque, A flange driving. The value has to be set by the user who is guided by the spreadsheets.

\( \tau_{BF2} \) Speed and load independent friction torque, B flange driving.

diameter Column vector of the wheels diameters.

\( N_{p1} \) Number of planets in the epicyclic stage.

\( N_{p2} \) Number of planets in the compound stage.

Temperature Indicates the nominal operating temperature of the reducer.

useTemperature Checkbox which enables the use of temperature dependent friction factors

\( Kf_0 \) Represent the efficiency loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.

\( Ks_0 \) Represent the speed loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.

\( Kt_0 \) Represent the tare loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.

\( x_{max} \) Matrix of polynomial coefficients used to correlate the variation of: \( Kf_0 \), \( Ks_0 \), \( Kt_0 \). This matrix represent the maximum increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.

\( x_{mean} \) Matrix of polynomial coefficients used to correlate the variation of: \( Kf_0 \), \( Ks_0 \), \( Kt_0 \). This matrix represent the mean increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.

\( x_{min} \) Matrix of polynomial coefficients used to correlate the variation of: \( Kf_0 \), \( Ks_0 \), \( Kt_0 \). This matrix represent the minimum increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.

Curves Is a parameter which allows the user to select from the three type of increase factors which one is to select to perform the calculations.

- Model interfaces and respective attached components

  **Mechanical:**

  flange_a Modelica standard flange in the rotational part of the mechanics interface library.

  flange_b Modelica standard flange in the rotational part of the mechanics interface library.
support  The support is used, when commanded by the user, to calculate the reaction torque necessary to maintain the reducer’s housing equilibrium.

Thermal:
Heat port can be connected to other component to propagate the heat flux.

### 7.4.8. Worm gear reducer

- **Engineering needs and relevant physical effects to be modeled**
  - **Basic function**: Mechanical power transmission.
  - **Structural pre-design**: Metallic material library used as source of material structural properties.
  - **Advanced physical effects**: Direct efficiency, Reverse efficiency, Breakout and running tare losses, Load independent drag torque, Speed dependent drag torque.

- **Fault conditions analyzed**: Bearing seizure, Lubricant contamination, Wear, Plastic deformation, Ductile fracture.

- **Interdependencies and links with other components**: Models can be arranged in series with themselves composing a multistage reducer, linked to external inertias, torques and speed sources.

- **Failure modes and their relevance**
  - Bearing seizure: mandatory
  - Wear: mandatory
  - Plastic deformation: optional
  - Ductile fracture: mandatory
  - Lubricant contamination: optional

- **Implementation levels and main model attributes**
  - **LEVEL 1**: Perfect power transformation without losses, torque and speed are modified according the speed ratio. If the wheels inertias are to be considered, the dynamic equilibrium equation is calculated.
  - **LEVEL 2**: The output torque of the driven side is now reduced by the speed losses due to the wheels windage. If the wheels inertias are to be considered, the dynamic equilibrium equation is calculated.
  - **LEVEL 3**: This level also considers the static friction torque acting on the shafts and calculates its sign and value using the hyperbolic tangent approach. If the wheels inertias are
to be considered the dynamic equilibrium equation is calculated.

LEVEL 4

The level 4 model is capable of reproducing the stuck condition whenever the driving torque is incapable of maintaining the reducer rotation. It also considers the temperature variation of efficiencies and loss parameters.

- Parameterization

**LEVEL 1:**

**General parameters**

- $z_s$: Number of starts of the worm. The value has to be set by the user.
- $z_2$: Number of teeth of the wheel. The value has to be set by the user.

**LEVEL 2:**

**General parameters**

- $z_s$: Number of starts of the worm. The value has to be set by the user.
- $z_2$: Number of teeth of the wheel. The value has to be set by the user.
- linearLosses: Checkbox which enables the linear losses calculations.
- $d_1$: Linear speed loss coefficient. The value has to be set by the user who is guided by the spreadsheets.
- $d_2$: Quadratic speed loss coefficient.

**LEVEL 3:**

**General parameters**

- $z_s$: Number of starts of the worm. The value has to be set by the user.
- $z_2$: Number of teeth of the wheel. The value has to be set by the user.
- linearLosses: Checkbox which enables the linear losses calculations.
- $d_1$: Linear speed loss coefficient. The value has to be set by the user who is guided by the spreadsheets.
- $d_2$: Quadratic speed loss coefficient.
- $\eta_{mf1}$: Direct efficiency. The value has to be set by the user who is guided by the spreadsheets.
- $\eta_{mf2}$: Reverse efficiency. The value has to be set by the user who is guided by the spreadsheets.
- $\omega_0$: Breakout speed. The value has to be set by the user who is guided by the spreadsheets.
- $T_{BF1}$: Speed and load independent friction torque, A flange driving. The value has to be set by the user who is guided by the spreadsheets.
- Lossygear: Checkbox which enables the use of two different speed and load independent friction torques in relation to which flange (A or B) is driving.
- $T_{BF2}$: Speed and load independent friction torque, B flange driving.

**LEVEL 4:**
**General parameters**

- \( z_s \)  
  Number of starts of the worm. The value has to be set by the user.

- \( z_2 \)  
  Number of teeth of the wheel. The value has to be set by the user.

- **linearLosses**  
  Checkbox which enables the linear losses calculations.

- \( d_1 \)  
  Linear speed loss coefficient. The value has to be set by the user who is guided by the spreadsheets.

- \( d_2 \)  
  Quadratic speed loss coefficient.

- \( \eta_{mf1} \)  
  Direct efficiency. The value has to be set by the user who is guided by the spreadsheets.

- \( \eta_{mf2} \)  
  Reverse efficiency. The value has to be set by the user who is guided by the spreadsheets.

- \( \omega_0 \)  
  Breakout speed. The value has to be set by the user who is guided by the spreadsheets.

- \( \tau_{BF1} \)  
  Speed and load independent friction torque, A flange driving. The value has to be set by the user who is guided by the spreadsheets.

- \( \tau_{BF2} \)  
  Speed and load independent friction torque, B flange driving.

- **Temperature**  
  Indicates the nominal operating temperature of the reducer.

- \( \alpha \)  
  Pressure angle of the threads and teeth of the worm.

- \( f \)  
  Dynamic friction coefficient at the worm/wheel interface.

- \( \gamma \)  
  Thread lead angle of the worm.

- **diameter**  
  Column vector of the wheels diameters.

- **useTemperature**  
  Checkbox which enables the use of temperature dependent friction factors

- \( K_{f0} \)  
  Represent the efficiency loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.

- \( K_{s0} \)  
  Represent the speed loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.

- \( K_{t0} \)  
  Represent the tare loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.

- \( x_{max} \)  
  Matrix of polynomial coefficients used to correlate the variation of: \( K_{f0} \), \( K_{s0} \), \( K_{t0} \). This matrix represent the maximum increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.

- \( x_{mean} \)  
  Matrix of polynomial coefficients used to correlate the variation of: \( K_{f0} \), \( K_{s0} \), \( K_{t0} \). This matrix represent the mean increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.

- \( x_{min} \)  
  Matrix of polynomial coefficients used to correlate the variation of: \( K_{f0} \), \( K_{s0} \), \( K_{t0} \). This matrix represent the minimum increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.

- **Curves**  
  Is a parameter which allows the user to select from the three type of increase factors which one is to select to perform the calculations.
• Model interfaces and respective attached components

**Mechanical:**
- **flange_a**: Modelica standard flange in the rotational part of the mechanics interface library.
- **flange_b**: Modelica standard flange in the rotational part of the mechanics interface library.
- **support_pinion**: The support is used, when commanded by the user, to calculate the reaction torque necessary to maintain the pinion equilibrium.
- **support_wheel**: The support is used, when commanded by the user, to calculate the reaction torque necessary to maintain the wheel equilibrium.

**Thermal:**
- **Heat port**: It can be connected to other component to propagate the heat flux, untimely, to the housing.

### 7.4.9. Bevel gear reducer

• Engineering needs and relevant physical effects to be modeled

  **Basic function**: Mechanical power transmission.
  **Structural pre-design**: Metallic material library used as source of material structural properties.
  **Advanced physical effects**:
  - Direct efficiency.
  - Reverse efficiency.
  - Breakout and running tare losses.
  - Load independent drag torque.
  - Speed dependent drag torque.

  **Fault conditions analyzed**:
  - Bearing seizure.
  - Lubricant contamination.
  - Wear.
  - Plastic deformation.
  - Ductile fracture.

• Interdependencies and links with other components:
  Models can be arranged in series with themselves composing a multistage reducer, linked to external inertias, torques and speed sources.

• Failure modes and their relevance
  - **Bearing seizure**: mandatory
  - **Wear**: mandatory
  - **Plastic deformation**: optional
  - **Ductile fracture**: mandatory
  - **Lubricant contamination**: optional
• Implementation levels and main model attributes

**LEVEL 1**
Perfect power transformation without losses, torque and speed are modified according the speed ratio. If the wheels inertias are to be considered, the dynamic equilibrium equation is calculated.

**LEVEL 2**
The output torque of the driven side is now reduced by the speed losses due to the wheels windage. If the wheels inertias are to be considered, the dynamic equilibrium equation is calculated.

**LEVEL 3**
This level also considers the static friction torque acting on the shafts and calculates its sign and value using the hyperbolic tangent approach. If the wheels inertias are to be considered the dynamic equilibrium equation is calculated.

**LEVEL 4**
The level 4 model is capable of reproducing the stuck condition whenever the driving torque is incapable of maintaining the reducer rotation. It also considers the temperature variation of efficiencies and loss parameters.

• Parameterization

**LEVEL 1:**
*General parameters*

\[ z_a \]  
Number of teeth of the pinion. The value has to be set by the user.

\[ z_b \]  
Number of teeth of the gear. The value has to be set by the user.

**LEVEL 2:**
*General parameters*

\[ z_a \]  
Number of teeth of the pinion. The value has to be set by the user.

\[ z_b \]  
Number of teeth of the gear. The value has to be set by the user.

\[ \text{linearLosses} \]  
Checkbox which enables the linear losses calculations.

\[ d_1 \]  
Linear speed loss coefficient. The value has to be set by the user who is guided by the spreadsheets.

\[ d_2 \]  
Quadratic speed loss coefficient.

**LEVEL 3:**
*General parameters*

\[ z_a \]  
Number of teeth of the pinion. The value has to be set by the user.

\[ z_b \]  
Number of teeth of the gear. The value has to be set by the user.

\[ \text{linearLosses} \]  
Checkbox which enables the linear losses calculations.

\[ d_1 \]  
Linear speed loss coefficient. The value has to be set by the user who is guided by the spreadsheets.

\[ d_2 \]  
Quadratic speed loss coefficient.

\[ \eta_{mf1} \]  
Direct efficiency. The value has to be set by the user who is guided by the spreadsheets.

\[ \eta_{mf2} \]  
Reverse efficiency. The value has to be set by the user who is guided by the spreadsheets.
Breakout speed. The value has to be set by the user who is guided by the spreadsheets.

\( \omega_0 \)

Speed and load independent friction torque, A flange driving. The value has to be set by the user who is guided by the spreadsheets.

\( T_{BF1} \)

Checkbox which enables the use of two different speed and load independent friction torques in relation to which flange (A or B) is driving.

\( \text{Lossygear} \)

Speed and load independent friction torque, B flange driving.

\( T_{BF2} \)

LEVEL 4:
General parameters

\( z_a \)

Number of teeth of the pinion. The value has to be set by the user.

\( z_b \)

Number of teeth of the gear. The value has to be set by the user.

\( \text{linearLosses} \)

Checkbox which enables the linear losses calculations.

\( d_1 \)

Linear speed loss coefficient. The value has to be set by the user who is guided by the spreadsheets.

\( d_2 \)

Quadratic speed loss coefficient.

\( \eta_{mf1} \)

Direct efficiency. The value has to be set by the user who is guided by the spreadsheets.

\( \eta_{mf2} \)

Reverse efficiency. The value has to be set by the user who is guided by the spreadsheets.

\( \omega_0 \)

Breakout speed. The value has to be set by the user who is guided by the spreadsheets.

\( T_{BF1} \)

Speed and load independent friction torque, A flange driving. The value has to be set by the user who is guided by the spreadsheets.

\( T_{BF2} \)

Temperature Indicates the nominal operating temperature of the reducer.

\( \psi \)

Angle comprised between the gear axis.

\( \text{diameter} \)

Column vector of the pinion and wheel diameter of the reducer.

\( \text{useTemperature} \)

Checkbox which enables the use of temperature dependent friction factors

\( K_{f0} \)

Represent the efficiency loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.

\( K_{s0} \)

Represent the speed loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.

\( K_{t0} \)

Represent the tare loss parameter of the reducer at the nominal operating temperature. Typical values are presented in the spreadsheets.

\( x_{\max} \)

Matrix of polynomial coefficients used to correlate the variation of: \( K_{f0}, K_{s0}, K_{t0} \). This matrix represent the maximum increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.
Matrix of polynomial coefficients used to correlate the variation of: $K_{f0}$, $K_{s0}$, $K_{t0}$. This matrix represents the mean increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.

Matrix of polynomial coefficients used to correlate the variation of: $K_{f0}$, $K_{s0}$, $K_{t0}$. This matrix represents the minimum increase factors for the three loss coefficients. The interpolation coefficient are contained in the spreadsheets.

Curves is a parameter which allows the user to select from the three type of increase factors which one is to select to perform the calculations.

- Model interfaces and respective attached components

**Mechanical:**
- flange_a
  Modelica standard flange in the rotational part of the mechanics interface library.
- flange_b
  Modelica standard flange in the rotational part of the mechanics interface library.
- support_pinion
  The support is used, when commanded by the user, to calculate the reaction torque necessary to maintain the pinion equilibrium.
- support_wheel
  The support is used, when commanded by the user, to calculate the reaction torque necessary to maintain the wheel equilibrium.

**Thermal:**
- Heat port
  It can be connected to other component to propagate the heat flux, untimely, to the housing.

### 7.4.10. Bearing Losses

The bearing model implements the additional losses for component, such as flexible or rigid shafts, which are supported in their rotation by roller bearings and connected to downdrives or directly to actuator gearboxes.

- Engineering needs and relevant physical effects to be modeled
  - Basic function: Mechanical power loss.
  - Structural pre-design: Presizing using the bearing sublibrary and database spreadsheets.
  - Advanced physical effects: Linear and exponential (less than linear) speed dependent losses, speed and load independent losses (Tare losses).
  - Fault conditions analyzed: Bearing seizure, Wear.

- Interdependencies and links with other components:
  Models can be arranged in series simulating the additional loss torque produced by the supports.

- Failure modes and their relevance
Bearing seizure mandatory
Wear mandatory

- Implementation levels and main model attributes
  LEVEL 1: Perfect power transmission without losses.
  LEVEL 2: Speed dependent losses, linear and exponential (less than linear).
  LEVEL 3: Speed dependent losses, linear and exponential (less than linear), constant speed and load independent friction torque (Tare loss).
  LEVEL 4: Speed dependent losses, linear and exponential (less than linear), speed and load independent friction torque (Tare loss) varying following a stribeck curve, temperature effect.

- Parameterization
  LEVEL 1: General parameters
  LEVEL 2: General parameters
    - linearLosses
      - If checked speed losses are taken into account.
    - speedLosses
      - Determines which equation for the speed loss calculation apply, linear, exponential (less than linear) or both.
    - $d_1$
      - Linear speed loss parameter.
    - $d_2$
      - Exponential (less than linear) speed loss parameter.
  LEVEL 3: General parameters
    - linearLosses
      - If checked speed losses are taken into account.
    - speedLosses
      - Determines which equation for the speed loss calculation apply, linear, exponential (less than linear) or both.
    - $d_1$
      - Linear speed loss parameter.
    - $d_2$
      - Exponential (less than linear) speed loss parameter.
    - $\omega_0$
      - Breakout speed.
    - $\tau_0$
      - Speed and load independent friction torque (Tare loss).
  LEVEL 4: General parameters
    - linearLosses
      - If checked speed losses are taken into account.
    - speedLosses
      - Determines which equation for the speed loss calculation apply, linear, exponential (less than linear) or both.
    - $d_1$
      - Linear speed loss parameter.
    - $d_2$
      - Exponential (less than linear) speed loss parameter.
    - $\omega_0$
      - Breakout speed.
tau<sub>0</sub> Speed and load independent friction torque (Tare loss).
useTemperature Boolean parameter which, if true, enables the use of temperature dependent friction parameters.
Temperature Temperature of the bearing.
ks<sub>0</sub> Exponential (less than linear) speed loss parameter at nominal temperature.
kt<sub>0</sub> Speed and load independent friction torque (Tare loss) at nominal temperature.
Peak Increase factor of tare loss parameter at breakout condition.
d<sub>2</sub><sub>geometry</sub> Speed loss coefficient increase factor, dependent by the geometry of the bearing.
tau<sub>0(geometry)</sub> Speed and load independent friction torque (Tare loss) increase factor, dependent by the geometry of the bearing.

- Model interfaces and respective attached components

**Mechanical:**
- flange_a Modelica standard flange in the rotational part of the mechanics interface library.
- flange_b Modelica standard flange in the rotational part of the mechanics interface library.
- support The support is used, when commanded by the user, to calculate the reaction torque necessary to maintain the bearing outer race in equilibrium.

**Thermal:**
Heat port can be connected to other component to propagate the heat flux.

### 7.4.11. Planar Gearwheels

The planar gearwheel models are used to simulate arbitrary spur gear configurations. The models only describe the gear contact. Using an external (free) planar library, it is possible to create gear configurations. These models are mainly interesting for very detailed analysis of the forces and moments or if vibration analysis are needed [12]. In the parts below, the models are described.

- Engineering needs and relevant physical effects to be modeled
  - Basic function Transformation of Moments and Forces. Calculation of transmission ratios
  - Vibration analysis (varying) contact stiffness and damping Failure introduction modifying gear stiffness

- Interdependencies and links with other components:
  - Without the PlanarMechanics library, the gear wheel models cannot be used

- Failure modes and their relevance
• Implementation levels and main model attributes

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic</td>
<td>Transmission only, no vibration analysis possible, no friction losses</td>
</tr>
<tr>
<td>Elastic</td>
<td>Including elastic effects, limited vibration analysis possible (no rattle), no friction losses</td>
</tr>
</tbody>
</table>

• Parameterization

All models have the following set of parameters:

- Gear radius gear A: \( r_A \)
- Gear radius gear B: \( r_B \)
- Animation switch: Animate
- StartAngle_a: Start Angle of gear A
- StartAngle_b: Start Angle of gear B
- Tooth_a: Number of Tooth gear A
- Tooth_b: Number of Tooth gear B
- RGB_a: Color (RGB values) of gear A
- RGB_b: Color (RGB values) of gear B
- zPosition: z position of the body
- zThickness: z thickness of the body

The elastic model has additional parameters:

- Gear contact stiffness: C
- Gear contact damping: D

Failure injection parameters:

- Enabling broken tooth simulation: Brokenthooth
- if table is defined on file or in function usertab this value must be set true
  - Stiffness matrix (grid = first column; e.g., table=[0,2]): gear_A_table
  - Table name on file or in function usertab: tableName_A
  - File where matrix is stored: fileName_A
- if table is defined on file or in function usertab this value must be set true
  - Stiffness matrix (grid = first column; e.g., table=[0,2]): gear_B_table
  - Table name on file or in function usertab: tableName_B
  - File where matrix is stored: fileName_B

• Model interfaces and respective attached components
• Expected numerical challenges
  Kinematic loops can lead to problems in systems without elasticity. Using an elastic system can help solving problems. Moreover, the use of backlash can lead to a stiff system, if a non-linear spring approach is used.

7.4.12. Differential Gearbox

• Engineering needs and relevant physical effects to be modeled

A differential gearbox offers the possibility to distribute power to or from two different load-paths. If the two load-paths are at the drive side, a redundant configuration is achieved i.e. in case one drive fails, the secondary load-path would still be active and drive the load. Differential gearboxes are common in high-lift systems, where a central power control unit comprising two independent motors drives a differential gearbox. The gearbox in turn drives a single shaft that extends to the high-lift transmission system of both wings. Therefore, in case one motor fails, the other one is still able to transmit power at half the nominal speed to the high-lift system.

The standard components of a spur-gears differential gearbox are a through-shaft together with the planetary gears carrier, the planetary gears and the side gears.

1. **Through-shaft/carrier**: The through-shaft and carrier are modeled together as a standard torque shaft assembly that transfers power to the planetary gears and to the subsequent shaft assembly on the main transmission drive shaft.

2. **Planetary gears**: The PGs are very stiff elements on which the tangential forces act on the same plane and consequently they do not undergo any torsional moments. These are therefore modeled as rigid bodies.

3. **Side gears**: The side gears are modeled as standard torque shafts since the acting tangential forces have different planes of action and produce a torsional moment.

![Figure 4: Differential Gearbox](image-url)
Physical Characteristics and Effects

a. Equations of motion
The differential gearbox is a two degree-of-freedom mechanism, one being the rotation about the axis of the through-shaft/carrier and side gears, and the other one about a perpendicular axis which corresponds to the planetary gears. For each degree of freedom different equations of motion apply. The motion of the through-shaft can be described similar to that of the standard torque shaft, hence

\[ J_{TS} \cdot \dot{\varphi}_{TS} = c_{TS} \cdot \left( \varphi_{in,TS} - \varphi_{out,TS} \right) + d_{TS} \cdot \left( \omega_{in,TS} - \omega_{out,TS} \right) - M_{SG1} - M_{SG2} - M_{f,TS} \]

where \( J_{TS} \) contains the moment of inertia of both the through-shaft and the planetary gears carrier. Moreover, \( M_{SG1} \) and \( M_{SG2} \) correspond to the resisting moments at the side gears which are transferred to the through-shaft by the planetary gears.

On the other hand, the motion of the side gears is coupled to the rotation of the through-shaft and planetary gears. Rotation of a planetary gear results from the summation of the moments acting about its rotational axis. The corresponding free body diagram is shown in Figure 5.

For the sake of simplicity, only one planetary gear is considered. Furthermore, the moment of inertia of one or more planetary gears is concentrated in a single term. The equation of motion for a single planetary gear is:

\[ J_{PG} \cdot \dot{\omega}_{PG} = F_{PG,2} \cdot r_{PG} - F_{PG,1} \cdot r_{PG} - M_{f,PG}. \]

All the components of the differential gearbox are subject to external friction generated by bearings. Therefore a frictional moment for both the through-shaft \( M_{f,TS} \) and planetary gears \( M_{f,PG} \) is considered. Backlash is also taken into account at the contact between them.

b. Power distribution
In order to completely describe the kinematics of the differential gearbox, one relationship for each degree of freedom has to be defined. For instance, the rotation of the side gears relative to the through-shaft/carrier is determined with the characteristic equation for planetary gearboxes:

\[ \frac{r_{SG2}}{r_{SG1}} = \frac{\omega_{SG1} - \dot{\varphi}_{TS}}{\omega_{SG2} - \dot{\varphi}_{TS}} \]

which expresses that the angular velocity of the carrier is always equal to that of the side gears as long as the planetary gears are locked. With rotation of the planetary gears, the velocity at the side gears either increases or decreases. The kinematic relationship in this case has to combine the rotation of both the through-shaft and the planetary gears.
The side gears, both rotating in the same direction, and one planetary gear of the differential gearbox are shown on the same plane in Figure 6 only for illustration purposes. The tangential velocity at point A is described by both the tangential velocity of the through-shaft $v_{TS}$ and the rotation of the planetary gears as:

$$v_{PG,A} = v_{TS} - \omega_{PG} \cdot r_{PG}$$

Transforming the linear velocities to circular motion by considering the fact that the tangential velocity of the planetary gear at point A is equal to that of side gear 1, yields

$$\omega_{SG1} \cdot r_{SG} = \omega_{TS} \cdot r_{SG} - \omega_{PG} \cdot r_{PG}$$

Furthermore, the side gears and carrier have the same rotational axis and radius, i.e. $r_{TS} = r_{SG}$. From the previous equations it is then possible to compute the angular velocity of each side gear to fully define the power distribution of the differential gearbox:

$$\omega_{SG1} = \omega_{TS} - \frac{r_{PG}}{r_{SG}} \cdot \omega_{PG}$$

$$\omega_{SG2} = 2 \cdot \omega_{TS} - \omega_{SG1}$$

c. Frictional and Thermal losses

All losses are inherited from the “Parallel Axis Spur Gears Reducer” model. These are used as replaceable models in the harmonic drive. The user can switch between different types of losses depending on the desired level of detail.

- **Interdependencies and links with other components:**
  a. The model can be connected to an input external inertia at both ports if no inertias are selected in the model.
  b. All losses are linked to those of the model “GearReducer” since it is used inside the Harmonic Drive model as replaceable.

- **Failure modes**
  - Jamming of side gears or through shaft/carrier
  - Disconnection of side gears or through shaft/carrier

- **Implementation levels and main model attributes**
  - **Basic**: functional model
    i. Kinematics
    ii. Inertia (selectable)
    iii. Torque transmission
- **Linear**: linear elastic behaviour and losses
  iv. Kinematics
  v. Inertia (selectable)
  vi. Torque transmission
  vii. Compliance
  viii. Linear friction (switchable)
  ix. Heat transfer (selectable)
  x. Failure modes

- **Nonlinear**: nonlinear elastic behaviour and losses
  xi. Kinematics
  xii. Inertia (selectable)
  xiii. Torque transmission
  xiv. Nonlinear compliance (backlash)
  xv. Nonlinear friction (switchable)
  xvi. Heat transfer (selectable)
  xvii. Failure modes

- **Parameterization**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Use and remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertia side gear 1</td>
<td>Inertia of right side gear with flange</td>
</tr>
<tr>
<td>Inertia side gear 2</td>
<td>Inertia of left side gear with flange</td>
</tr>
<tr>
<td>Inertia planets</td>
<td>Inertia of planetary gears</td>
</tr>
<tr>
<td>Inertia through shaft/carrier</td>
<td>Is the inertia of the shaft crossing through the differential gearbox together with a mounted planetary gears carrier</td>
</tr>
<tr>
<td>Reduction ratio</td>
<td>Reduction ratio of side gears to planetary gears</td>
</tr>
<tr>
<td>Compliance SG1, SG2</td>
<td>Compliance of side gear flanges</td>
</tr>
<tr>
<td>Structural damping SG1, SG2</td>
<td>Structural damping of side gear flanges</td>
</tr>
<tr>
<td>Through shaft compliance</td>
<td>Compliance of through shaft together with planetary gears carrier</td>
</tr>
<tr>
<td>Through shaft structural damping</td>
<td>Structural damping of through shaft together with planetary gears carrier</td>
</tr>
<tr>
<td>Side gears backlash</td>
<td>Backlash between side gears and planetary gears</td>
</tr>
<tr>
<td>Frictional parameters</td>
<td>See section 7.4.3</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>Temperature around the device</td>
</tr>
</tbody>
</table>

**Initial conditions**

- Relative initial rotation angle: 0 deg
- Relative initial rotation speed: 0 deg/s
**Parameter records according to modeling level:**

<table>
<thead>
<tr>
<th>Modeling Level</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic</td>
<td>Reduction ratio $i [-]$</td>
</tr>
<tr>
<td></td>
<td>Side Gears, Planets, Through Shaft Inertias $J_{SG1,SG2,p,ts}$ [kg·m^2] (selectable)</td>
</tr>
<tr>
<td>Linear</td>
<td>Basic + …</td>
</tr>
<tr>
<td></td>
<td>Side Gears and Through Shaft Compliances $c_{SG1,SG2,ts}$ [N·m/rad]</td>
</tr>
<tr>
<td></td>
<td>Structural damping parameters $d_{SG1,SG2,ts}$ [Nm·s/rad]</td>
</tr>
<tr>
<td></td>
<td>Linear friction parameters (see section 7.4.3)</td>
</tr>
<tr>
<td></td>
<td>Ambient Temperature $T_a$ [°C]</td>
</tr>
<tr>
<td>Nonlinear</td>
<td>Linear + …</td>
</tr>
<tr>
<td></td>
<td>Backlash angle between Side Gears and Planets $\phi_{bl}$ [deg]</td>
</tr>
<tr>
<td></td>
<td>Nonlinear friction parameters (see section 7.4.3)</td>
</tr>
</tbody>
</table>

- Model interfaces and respective attached components
  d. One drive unit (e.g. electric motor) connected to the through shaft or one drive unit connected to each side gear
  e. Mechanical support
  f. Thermal port to heat sink

### 7.4.13. Ball-Ramps Torque Limiter

- Engineering needs and relevant physical effects to be modeled

A ball-ramps torque limiter is a device which is usually placed between two sections of a mechanical transmission system designed for different load levels. The torque limiting device protects the section designed for lower loads by engaging and grounding the drive torque to a structural part in case upstream overloads are present.

**Physical Characteristics and Effects**

- Equations of motion

The interaction between the two mechanical components that allow for torque limiting i.e. sliding coupling and friction disc pack is illustrated in Figure 7, along with the output shaft on which the brake moment is applied.

![Figure 7: Ball-Ramps Torque Limiter](image)
Sliding coupling: The sliding coupling is the means for engaging the torque limiter friction disc packs. Under nominal operation of the transmission system, it remains in a first contact phase CP1 (see Figure 8), and behaves as a normal torque shaft that transfers the corresponding driving torque. However, the purpose of the sliding coupling is to provide an axial displacement resulting from the relative motion between its input and output upon the presence of an extensive upstream moment.

![Figure 8: Characteristic Behavior of a Ball-Ramps Torque Limiter](image)

If this is the case, the coupling’s stiffness is largely reduced as it goes through a sliding phase SP. This happens when the balls move up the ramps. When the lockout moment \( M_{TL,UR} \) is reached, the stiffness of the sliding coupling is that of the second contact phase CP2. Under these considerations, a sliding coupling can be modeled as a “standard torque shaft” with non-linear stiffness. The stiffness of the sliding coupling is described by the slope of the characteristic line shown in Figure 8. The torsional moment \( M_{t,SC} \) is interpolated using moment values corresponding to the torque limiter settings at a certain angle of twist \( \Delta \varphi_{SC} \) of the sliding coupling. Initially, a certain stiffness \( c_{cp} \) for the first contact phase of the sliding coupling is chosen similar to that of adjacent components. The equation of motion of the sliding coupling is:

\[
J_{SC} \cdot \dot{\varphi}_{out} = M_{t,SC}(\Delta \varphi_{SC}) - M_{in} - M_{f,SC}
\]

Friction disc pack: The moment produced by the friction disc packs that perform the torque limiting action can be considered as an additional frictional moment \( M_{f,TL} \) on the component of application. This one is only activated when the sliding coupling moves into the positive or negative sliding phases, that is, when a relative angular position \( \varphi_{SP} \) between the sliding coupling’s input and output is reached. The moment \( M_{f,TL} \) produced by the torque limiter is modeled using a stiffness \( c_{f,TL} \) which characterizes the magnitude of the brake moment with increasing \( \Delta \varphi_{SC} \).

\[
M_{f,TL} = \begin{cases} 
0 & \text{if } \varphi_{SP}^- < \Delta \varphi_{SC} < \varphi_{SP}^+; \\
(c_{f,TL} \cdot (\Delta \varphi_{SC} - \varphi_{SP})) & \text{if } |\Delta \varphi_{SC}| \geq \varphi_{SP}.
\end{cases}
\]

When the lower torque limiter setting \( M_{TL,Low} \) is surpassed, the brake moment starts being applied. By reaching the upper torque limiter setting \( M_{TL,Up} \), the balls move completely out the ramps and the sliding coupling proceeds to the second contact phase. The output shaft of the torque limiter can be modeled as a standard torque shaft with:

\[
J_{OS} \cdot \dot{\varphi}_{out} = \frac{c_{OS} \cdot (\varphi_G' - \varphi_{out}) + d_{OS} \cdot (\omega_G' - \omega_{out})}{M_{t,OS}} - M_{in} - M_{f,S} - M_{f,TL}
\]

b. Frictional and Thermal losses

The thermal losses arising from the friction discs are transported in form of heat through a thermal port.
Interdependencies and links with other components:
  a. The torque limiter model can be connected to an input external inertia if no inertias are selected in the parameter window.

Failure modes
  • None.

Implementation levels and main model attributes
  - **Nonlinear:** nonlinear braking/frictional behaviour and losses
    i. Inertia (selectable)
    ii. Torque transmission
    iii. Nonlinear compliance (ball-ramp characteristic)
    iv. Friction disc-packs braking
    v. Heat transfer (selectable)

Parameterization

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Use and remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertia</td>
<td>Inertia of right side gear with flange</td>
</tr>
<tr>
<td>Nominal compliance</td>
<td>Inertia of left side gear with flange</td>
</tr>
<tr>
<td>Compliance during sliding phase</td>
<td>Inertia of planetary gears</td>
</tr>
<tr>
<td>Compliance at lock-out</td>
<td>Is the inertia of the shaft crossing through the differential gearbox together with a mounted planetary gears carrier</td>
</tr>
<tr>
<td>Torque setting at start of lock-out process</td>
<td>Reduction ratio of side gears to planetary gears</td>
</tr>
<tr>
<td>Torque setting at start of braking process</td>
<td>Compliance of side gear flanges</td>
</tr>
<tr>
<td>Structural damping</td>
<td>Structural damping of side gear flanges</td>
</tr>
<tr>
<td>Max. braking force</td>
<td>Compliance of through shaft together with planetary gears carrier</td>
</tr>
<tr>
<td>Positive sliding friction coefficient</td>
<td>Structural damping of through shaft together with planetary gears carrier</td>
</tr>
<tr>
<td>Maximum sliding friction</td>
<td>Backlash between side gears and planetary gears</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>Temperature around the device</td>
</tr>
</tbody>
</table>

Initial conditions

| Relative initial rotation angle | 0 deg |
| Relative initial rotation speed | 0 deg/s |
Parameter records according to modeling level:

<table>
<thead>
<tr>
<th>Modeling Level</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>Nominal compliance $c_{\text{nom}}$ [N·m/rad]</td>
</tr>
<tr>
<td></td>
<td>Lockout compliance $c_{\text{lockout}}$ [Nm·s/rad]</td>
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<tr>
<td></td>
<td>Transition phase compliance $c_{\text{slide}}$ [Nm·s/rad]</td>
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<td></td>
<td>Torque for start of lockout process $\tau_{\text{lockout}}$ [Nm]</td>
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<tr>
<td></td>
<td>Torque at start of braking process $\tau_{\text{TorqueLimit}}$ [Nm]</td>
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<td></td>
<td>Nominal structural damping $d$ [Nm·s/rad]</td>
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<tr>
<td></td>
<td>Maximum braking normal force $f_{\text{nm}}$ [N]</td>
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<tr>
<td></td>
<td>Sliding friction coefficient $\mu_{\text{pos}}$</td>
</tr>
<tr>
<td></td>
<td>Maximum sliding friction coefficient $\mu_{\text{peak}}$</td>
</tr>
<tr>
<td></td>
<td>Friction distribution constant $c_{\text{geo}}$</td>
</tr>
</tbody>
</table>

- Model interfaces and respective attached components
  - c. High load transmission section connected to flange_a
  - d. Low load transmission section connected to flange_b
  - e. Mechanical support
  - f. Heat sink connected to thermal port

7.5. Sensors

Sensors are needed to control the dynamic performance of the EMA and to look after its status (often through temperature measurements). MSL contains ideal sensor models. The aim of the sensor models developed in WP31 is to add real effects and faults to the sensor signal in order to analyze how they affect to the EMA operation.

The following sensors are included in the A2015 library:
- Angular position sensors.
- Linear position sensors.
- Angular speed sensors.
- Torque sensors.
- Force sensors.
- Current sensors, single-phase and multi-phase.
- Temperature sensors.

No specific sensor technology is indicated (LVDT, Hall effect sensor, etc.) because, as mentioned later, sensors are modelled in a functional way.

7.5.1. Parameterization and functional modelling of sensors

WP31 library is a multiphysics library for simulation of complete EMA’s. Very different physical and technical areas are involved (mechanical, electrical motors, power electronics, and sensors), so the priority is to have models which do not require specific knowledge from the component design point of view. For that reason, a very concrete requirement is defined for WP31 model developers: the parameters of the models should be those you could find in a typical data sheet.
In the case of sensors, the user parameters are the performance characteristics of the sensor (measurement range, sensitivity, resolution, and others that will be detailed later), which do not have direct relation with sensor design features. By way of example, let’s see that for an LVDT sensor:

Like most sensors, LVDT is composed by a transducer and the electronics required for both the power supply and the transducer’s output signal conditioning, which allows easier interpretation of the sensor reading. The LVDT transducer is a transformer with two secondary windings whose induced voltages vary with the translation of the rod attached to the element that must be measured. The ideal LVDT transducer is represented in Figure 9, and its equations are given below:

![Figure 9: Ideal LVDT transducer](image)

\[ v_1 = L_1 \frac{di}{dt} + M_{2a} \frac{dM}{dt} + M_{2b} \frac{dM}{dt} \]  

\[ v_{2a} = M_{2a} \frac{di}{dt} + L_{2a} \frac{dM}{dt} \]  

\[ v_{2b} = M_{2b} \frac{di}{dt} + L_{2b} \frac{dM}{dt} \]  

For model completeness, the value of the inductances \((L_1, L_{2a}, L_{2b}, M_{2a}, M_{2b})\) and their variation (mainly \(M_{2a}\) and \(M_{2b}\)) with rod position \(s\) must be defined. One option is to directly ask to the user of the model for the value and variation function of each inductance. Another option is to ask to the user for the geometry and physical properties of the transducer, and the model would estimate the inductances and variation functions [13]. In any case, the parameters the user should define are too specific from the LVDT design point of view.

The previous example (which is only the simplest model of an LVDT) clearly shows that a physical sensor model requires parameters that are not practical from the end-user point of view. At the same time, the electronics integrated in the sensor is designed and/or programmed to compensate unwanted transducer effects in order to provide a sensor signal as ideal as possible (linear with respect to the input). To some extent, physical meaning is lost from the end-user point of view and only sensor performance characteristics are given to the end-user. In fact, the performance characteristics of all sensors, no matter the sensor category (linear position, angular position, force,...) or technology (LVDT, Hall-effect,...), are given in the same “language”, that is, using the same parameters.

**Functional modelling**

Considering the physical modelling issues addressed before with respect to the parameters wanted for WP31 sensor models, a functional modelling approach will be used, i.e., not the sensor physical behaviour but the effects on the output sensor signal will be modelled. For example, sensor sensitivity (output sensor signal variation when measured variable changes) is the main effect to be considered. From a functional point of view, the actual sensitivity is got by combination of the sensitivity constant (taken as parameter from the datasheet) with the effects affecting it (e.g. temperature).
More information about the effects addressed in the sensor sublibrary is given in the next paragraphs.

### 7.5.2. Sensor model specification

- **Engineering needs and relevant physical effects to be modeled**
  
  Sensor models replicate the real effects on the sensor reading in order to analyze their consequence on the dynamic control or security of the EMA.

Some of these effects are usually called faults because they do not exist on an ideal sensor; however they are inherent to the sensor, so strictly speaking they are not faults. To avoid confusions, the name “fault” will be used in this document only for strict faults, not for those real effects also present in non-fault conditions.

Below indicated effects are present on the sensor models’ output signals:

- **Sensitivity**: output sensor signal change due to a change of the measured variable. It is the fundamental effect in a sensor (with analogue transducers of course, not as digital sensors like encoders) and some of the effects addressed next have influence on it.
- **Offset**: sensor output value when the measured variable has null value.
- **Non-linearity**: non constant sensitivity over the measurement range.
- **Saturation**: Maximum value of the output sensor signal, as well as smooth transition from the linear range to the saturated value. It is a kind of non-linearity, but only around and due to the sensor’s measurement range limits.
- **Hysteresis**: it causes different output sensor signal for the same value of the measured variable when this is increasing or decreasing.
- **Noise**: time-variable random signal (often of high-frequency) superposed to the output sensor signal.
- **Drift**: instability of the output sensor signal when the measured variable and environmental conditions do not change. Though drift causes the same effect as noise does, they are different concepts. The origin of noise is usually external to the sensor and of high-frequency, whereas drift’s origin is internal and causes a slow variation in the output signal.
- **Delay**: Time delay on the sensor output signal refresh after a change of the measured variable.
- **Temperature** affects some of the previous effects (sensitivity and offset).
- Effects due to **discretization** of the sensor signal:
  - Sampling (or time discretization).
  - Quantization (or value discretization).
  - Time delay due to sampling process.

- **Interdependencies and links with other components**

  Each sensor model must be simply connected to the physical interface where the variable has to be measured. No more is needed for the sensor models to work, neither electrical supply nor output signal conditioning, because of the need for end-user orientation instead of sensor design orientation.
- Failure modes and their relevance

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Effect</th>
<th>Relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open circuit</td>
<td>Signal loss</td>
<td>mandatory</td>
</tr>
<tr>
<td>Short circuit</td>
<td>Zero signal</td>
<td>mandatory</td>
</tr>
<tr>
<td>Intermittent dropouts</td>
<td>Intermittent signal losses</td>
<td>optional</td>
</tr>
<tr>
<td>Stuck-in-range</td>
<td>Frozen (locked) sensor reading during a certain period</td>
<td>optional</td>
</tr>
</tbody>
</table>

- Implementation levels and main model attributes

The table below classifies the effects according to the modelling levels agreed for WP31 library.

<table>
<thead>
<tr>
<th>Level</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>- Constant sensitivity.</td>
</tr>
<tr>
<td>2</td>
<td>- Constant offset.</td>
</tr>
<tr>
<td></td>
<td>- Linear variable sensitivity with temperature.</td>
</tr>
<tr>
<td></td>
<td>- Linear variable offset with temperature.</td>
</tr>
<tr>
<td></td>
<td>- Linear drift.</td>
</tr>
<tr>
<td>3</td>
<td>- Non-linearity in the measurement range.</td>
</tr>
<tr>
<td></td>
<td>- Saturation (non-linearity near the measurement range limits).</td>
</tr>
<tr>
<td></td>
<td>- Non-linear drift.</td>
</tr>
<tr>
<td>4</td>
<td>- Hysteresis.</td>
</tr>
<tr>
<td></td>
<td>- Delay.</td>
</tr>
<tr>
<td></td>
<td>- Discretization: amplitude and time discretization, and computational delay.</td>
</tr>
<tr>
<td></td>
<td>- Noise.</td>
</tr>
</tbody>
</table>

- Parameterization

The parameters the user has to define for sensor models are directly related to the effects on the sensor signal he wants to activate, they are listed in the following paragraph.
<table>
<thead>
<tr>
<th>Effect</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>Sensitivity constant.</td>
</tr>
<tr>
<td>Constant offset</td>
<td>Offset value.</td>
</tr>
<tr>
<td>Linear variable sensitivity with T</td>
<td>Temperature coefficient of the sensitivity.</td>
</tr>
<tr>
<td>Linear variable offset with T</td>
<td>Temperature coefficient of the offset.</td>
</tr>
<tr>
<td>Linear Drift</td>
<td>Time coefficient of the drift evolution.</td>
</tr>
<tr>
<td>Non-linearity</td>
<td>Non-linearity function or curve.</td>
</tr>
<tr>
<td>Saturation</td>
<td>Maximum limits of the output signal.</td>
</tr>
<tr>
<td>Non-linear drift</td>
<td>Points defining the time dependent drift curve.</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>Hysteresis band.</td>
</tr>
<tr>
<td>Delay</td>
<td>Delay time.</td>
</tr>
<tr>
<td>Sampling</td>
<td>Quantization is defined by measurement range (minimum and maximum values) and the number of bits.</td>
</tr>
<tr>
<td>Sampling frequency is defined by the clock connected to the sensor.</td>
<td>A computational delay can be inserted as a fraction of the clock period.</td>
</tr>
<tr>
<td>Noise</td>
<td>Noise amplitude.</td>
</tr>
</tbody>
</table>

- Model interfaces and respective attached components
  Each sensor model has:
  - Input/output ports connected to the component to be measured:
    a) Linear position sensor model has a mechanical translational input port, and an optional mechanical translational output port to be activated when relative position wants to be measured. If this optional output port is deactivated, the position of the input flange is measured respect to a fixed support defined inside the sensor model.
    b) Angular position sensor model has analogous interface to linear position sensor but with mechanical rotational ports.
    c) Angular speed sensor model has same interface as angular position sensor model.
    d) Force sensor model has same interface as linear position sensor model.
    e) Torque sensor model has same interface as angular position sensor model.
    f) Single-phase current sensor model has one electrical input and one electrical output port. Multi-phase current sensor model has “m” electrical input and output ports, “m” being the number of phases.
    g) Temperature sensor model has a single thermal input port.
  - Conditional thermal port, to be activated when sensor’s temperature dependence is to be considered. In the temperature sensor model, of course, this port is not conditional and is the same one defined above as main input port.
  - Output signal bus with three predefined signals:
    1. Real sensor signal, with all the non-ideal effects and faults.
    2. Ideal sensor signal, which may be useful for the user developing a control algorithm such that he does not have to re-parameterize or change model levels of the plant model and still access the ideal sensor signal.
    3. Sensor status flag, which indicates whether the sensor is on a fault mode or not.
• Expected numerical challenges
  Models in this part of the library do not have considerable impact on simulation performance. Sensor signal discretization and fault injections are the only sources that trigger events.

7.6. Thermal components: Heat-sinks

• Engineering needs and relevant physical effects to be modeled
  Heat sinks are used to remove the heat generated by power electronic devices more effectively than they will do themselves. Modelling heat sinks as independent components, not inside those power electronic devices, besides contributing to the modularity and flexibility of the library, allows having multiple power electronic devices connected to one heat sink, which is very common, especially in aerospace.

  Within the scope of WP3.1, the needs that have been defined for heat sink models are:
  - Both natural and forced cooling methods are considered.
  - The models are general enough to use different coolant types (air and water are the most common). Heat sinks basically have an inlet and outlet and any fluid can be put in and taken out. The models, however, for generalization and easy parameterization, do not use physical ports (inlet or outlet) for the fluid. The only difference air/liquid makes is how quickly the heat is removed, which is modelled by the curves provided in datasheets.
  - The physical effects involved are the thermal storage and thermal resistance of the heat sink.

• Interdependencies and links with other components
  Heat sink models have a thermal port to be connected to the power electronic devices to be cooled, and a second thermal port to be connected to the coolant temperature. Models with forced cooling have an additional numerical input defining the coolant flow rate (air speed in m/s for fan cooling, or volume flow rate in m³/s for liquid cooling) in order to make possible a controller to control that flow rate as a function of the temperature.

• Failure modes and their relevance
  Failures on heat sinks are very unlikely. However, the most frequent are considered in these models. A heat sink may be disconnected from the power electronic device. In terms of forced cooling, the fan could break and revert to natural cooling, or the flow of liquid could stop due to the pump failure.

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Effect</th>
<th>Relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disconnection of the heat sink from the converter</td>
<td>Increase of thermal resistance</td>
<td>mandatory</td>
</tr>
<tr>
<td>Fan or pump stop</td>
<td>Transition from forced to natural convection</td>
<td>mandatory</td>
</tr>
</tbody>
</table>

• Implementation levels and main model attributes
  Heat sink models make a polynomial fitting of the points taken by the user from datasheet curves, so the order of the polynomial is \( n = p - 1 \) (\( p \) is the number of given points). Then, the model will have a different level depending on the number of points given:
p = 1 \rightarrow n = 0. This will be a level 1 model, a simple thermal resistance, which would be the same model as “Convection” or “ThermalConductor” available in the MSL (Modelica.Thermal.HeatTransfer.Components).

p = 2 \rightarrow n = 1 \rightarrow Linear model, invertible \rightarrow level 2.

p \geq 3 \rightarrow n \geq 2 \rightarrow Non-linear model, non-invertible \rightarrow According to the levels defined in Actuation2015, this would be a level 4 model. However, it is not a hard-non-linear model at all. In fact, it is always derivable because uses the Modelica standard “evaluate” function (Modelica.Media.Incompressible.TableBased.Polynomials_Temp.evaluate), which has the derivative function defined in its annotation.

Parameterization
- For natural cooling the user must define points of the curve “thermal resistance vs. power dissipation”.
- In the forced cooling case, “thermal resistance vs. air speed” or “thermal resistance vs. liquid flow rate” curve is used.

Those data are fitted to a continuous function (polynomial) which is used to determine the actual resistance taking into account the operating conditions (temperature and fluid flow rate).

Model interfaces and respective attached components
- Thermal port
  - Connected to the component to be cooled
- Thermal port
  - Connected to the ambient or coolant
- Real input (only in active cooled heat sinks)
  - Coolant flow rate value

7.7. Communication buses

Numerous electrical signals flow inside an EMA, so the amount of connection lines between the EMA component models in an EMA model would be large and difficult to manage. For that reason, in order to facilitate the definition and simulation of EMA models, models for the most common buses will be included in WP3.1 library, and their connectors will be predefined with the signals transmitted through them. That way, multiple signals are compiled and managed by single bus lines, and also the user has not to add additional signals in the most common cases. Anyway, as the variety of practical cases is in order to keep flexibility and easy usage of models, bus models will be implemented with “expandable” type connectors, which allow the user to add any not predefined signal by simply connecting it to the bus.

With regard to the specifications for the bus models:
- Buses are modelled in a functional way (as sensors) to provide the user with easily manageable models where real effects can be activated without going into too specific communication issues.
- The effects to be considered are signal discretization, transmission delays, and noise.
- The interfaces are connectors with multiple signals.

Both the modelling approach and the effects are common to sensor models, so details about implementation levels, parameterization and expected numerical challenges can be found in chapter 7.5.
7.7.1. Predefined buses and signal population

A minimum set of EMA buses and signal population to be implemented in WP3.1 library have been agreed among project partners. Two groups of predefined buses will be considered:

a) Standard buses for simple actuators: they include the signals to be transmitted between the electro-mechanical components (motor and mechanical actuator) and the control system.

b) Buses for advanced EMAs. These will include buses for specific and advanced EMA architectures. As said before, multiple architectures could be, so not all them can be considered and included in the library. One of them is detailed next (Figure 10 and section 7.7.3) as example, which corresponds to the EMA architecture and signal distribution defined for Actuation2015.

![Figure 10: Buses in advanced EMA system](image)

A detailed list of the buses and predefined signals to be considered is given below, with the definition of each bus interface or connector.

Each signal measured in the EMA is transmitted through the corresponding sensor bus. Each sensor bus has 3 signals: Ideal signal, real signal, and status flag.

<table>
<thead>
<tr>
<th>Sensor bus interface</th>
<th>Ideal signal</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real signal</td>
<td>yMod</td>
<td></td>
</tr>
<tr>
<td>Status flag</td>
<td>valid (boolean: true or false)</td>
<td></td>
</tr>
</tbody>
</table>

| Motor sensor bus signals | | |
|--------------------------|-----------------|
| Currents sensor bus signals | i | iMod |
| Motor position sensor bus signals | Phi | phiMod |
| Motor temperature sensor bus signals | T | TMod |

7.7.2. Standard buses for simple actuators

Motor sensor bus

The motor sensor bus includes measured currents, position and temperature of the motor.
Motor bus

The motor bus includes motor sensor bus signals as well as motor current references coming from a controller.

<table>
<thead>
<tr>
<th>Table 3: Motor bus interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor bus interface</td>
</tr>
<tr>
<td>From motor</td>
</tr>
<tr>
<td>Motor sensor bus</td>
</tr>
<tr>
<td>From controller</td>
</tr>
<tr>
<td>Motor current demands</td>
</tr>
<tr>
<td>iq_ref</td>
</tr>
<tr>
<td>id_ref</td>
</tr>
</tbody>
</table>

Actuator sensor bus

The actuator sensor bus includes only the motor sensor bus signals as predefined. The actuator position is expected to be connected by the user, but it is not predefined because the position can be linear or rotational depending on the type of the actuator.

Actuator bus

The actuator bus includes motor bus signals as well as actuator position and speed references coming from a controller.

<table>
<thead>
<tr>
<th>Table 4: Actuator bus interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuator bus interface</td>
</tr>
<tr>
<td>Motor bus</td>
</tr>
<tr>
<td>Speed reference</td>
</tr>
<tr>
<td>w_ref</td>
</tr>
<tr>
<td>Position reference</td>
</tr>
<tr>
<td>phi_ref</td>
</tr>
</tbody>
</table>

7.7.3. An example of buses for Advanced EMAs

This section shows the buses for the specific EMA architecture shown in Figure 10 by way of example of what can be done with the library.

Translational and rotational actuators’ sensor bus interfaces

<table>
<thead>
<tr>
<th>Table 5: Translational (a) and Rotational (b) actuator sensor bus interfaces</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Translational actuator’s sensor bus interface</td>
</tr>
<tr>
<td>Translational Actuator’s sensor bus interface</td>
</tr>
<tr>
<td>Actuator position sensor</td>
</tr>
<tr>
<td>sMod valid</td>
</tr>
<tr>
<td>Actuator load sensor</td>
</tr>
<tr>
<td>fMod valid</td>
</tr>
<tr>
<td>b) Rotational actuator’s sensor bus interface</td>
</tr>
<tr>
<td>Rotational Actuator’s sensor bus interface</td>
</tr>
<tr>
<td>Actuator position sensor</td>
</tr>
<tr>
<td>phiMod valid</td>
</tr>
<tr>
<td>Actuator torque sensor</td>
</tr>
<tr>
<td>tauMod valid</td>
</tr>
</tbody>
</table>

a) Translational actuator’s sensor bus interface

<table>
<thead>
<tr>
<th>Translational Actuator’s sensor bus interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translational Actuator’s sensor bus interface</td>
</tr>
<tr>
<td>Actuator position sensor</td>
</tr>
<tr>
<td>sMod valid</td>
</tr>
<tr>
<td>Actuator load sensor</td>
</tr>
<tr>
<td>fMod valid</td>
</tr>
<tr>
<td>b) Rotational actuator’s sensor bus interface</td>
</tr>
<tr>
<td>Rotational Actuator’s sensor bus interface</td>
</tr>
<tr>
<td>Actuator position sensor</td>
</tr>
<tr>
<td>phiMod valid</td>
</tr>
<tr>
<td>Actuator torque sensor</td>
</tr>
<tr>
<td>tauMod valid</td>
</tr>
</tbody>
</table>
CMM-PCM bus interface

CMM-PCM bus includes:

From CMM to PCM:
- Duty-cycle requests.

From PCM to CMM:
- HVDC voltage and current.
- Motor currents, position, and temperature.

Table 6: CMM-PCM interface

<table>
<thead>
<tr>
<th>CMM-PCM bus interface</th>
<th>Motor current demand</th>
<th>Motor speed demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMM -&gt; PCM</td>
<td>i1_ref (duty cycle)</td>
<td>w_ref (duty cycle)</td>
</tr>
<tr>
<td>PCM -&gt; CMM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMM-PCM bus interface</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FCC-CMM bus interface

FCC to CMM bus:
- Measurement signals:
  - Rod position.
  - Surface position.
- Control signals:
  - Rod position reference.
  - Surface position reference.

Status signals [14]:
- Actuator mode status: it is reported through specific bit(s) allocated in the BIT status word: Active, Damping, Passive, Follower, RAT.
- Signals for health monitoring: the failure status of some components (motor drive and several sensors) is reported through specific bit(s) allocated in the BIT status word.
7.8. Controllers

Controllers are necessary for shaping the transient characteristics of EMAs, suppressing the effects of measurement noises and disturbances. Single EMAs are usually controlled in a cascade fashion using different kinds of controllers. Moreover, force fight compensation due to small differences between the EMAs is also a key problem that has to be solved. The objective of this package is to provide the designer with the blocks that make EMA control design and analysis convenient.

Apart from standard P/PD/PI/PID, dedicated current, speed and position controllers, various filter blocks, the package provides building blocks that make the assessment of various fault effects convenient.

Furthermore, the package contains a collection of MATLAB functions, the purpose of which is to enable the user to utilise advanced control and health monitoring design methods available within the MATLAB/Simulink environment.

- Engineering needs and relevant physical effects to be modeled
  - Basic function: basic controller blocks
    - continuous P/PI/PD/PID
    - discrete P/PI/PD/PID
  - Specialised controller blocks
    - current controller
    - speed controller
    - position controller (rotational & translational)
    - force fight compensator

- Advanced effects: integrator anti-windup
- output saturation
- Fault condition analysed
  - freeze (constant output)
  - reset (internal states reset to initial values)
  - spikes (1-2 sample long large values)
  - non-return to zero (output switching between minimum and maximum)
  - runaway (output gradually reaches output limit and does not change afterwards)

| Table 7: FCC-CMM bus interface |
|-------------------------|------------------|
| Rod position sensor bus | valid |
| Surface position sensor bus | valid |
| Rod position reference | sRodRef |
| Surface position reference | sSurfRef |
| Actuator mode status word | Active |
| RAT |
| Component failure status | Motor drive status |
| Motor position sensor status |
| Motor temperature sensor status |
| Actuator position sensor status |
| Actuator load sensor status |
• Interdependencies and links with other components:
  Control related models in this library make use of blocks from the ModelicaSynchronous and Modelica_LinearSystems2 libraries. Controller blocks dedicated to specific purposes (current control, speed control, etc.) can be connected to each other via specialised bus interfaces (see chapter 6.7).

• Implementation levels and main model attributes
  Basic simple functionality of controllers built up from P, I, D blocks
  Discontinuities consider control output ranges
  integrator anti-windup

• Failure modes and their relevance
  Freeze mandatory
  Reset mandatory
  Spikes mandatory
  Non-return to zero mandatory

• Parameterization

  Internal controller blocks
  All internal controller blocks have full functionality. However, only basic parameters are active by default. These blocks can be parameterized according to either the serial or the parallel convention. The blocks may also be parameterised via dedicated parameter records.

  **Basic parameters**

  **Continuous-time**
  
  Ap controller gain
  kP proportional gain (default = 1)
  Ti integrator time constant
  Td derivative time constant
  Tdcorr auxiliary derivative time constant (default = 0.1*Td)
  int_initType initialisation type of the integrator (choices:
  no initialisation, steady state, specified initial output)
  int_y_start initial output of the integrator
  der_initType initialisation type of the derivative (choices:
  no initialisation, steady state, specified initial state, specified initial output)
  der_x_start initial state of the derivative
  der_y_start initial output of the derivative
Discrete-time

Ts    sampling time
Ap    controller gain
kP    proportional gain (default = 0)
kI    integrator gain
kD    derivative gain
int_start    initial output of the integrator
der_start    initial output of the derivative

Saturation parameters

controlMax    maximum controller output (symmetric about 0)
AwLimit    limit above which integration anti-windup is enabled
kAw    anti-windup gain

Fault parameters

Each fault model contains a fault source block. This block can be parameterised according to the convention of the FaultTriggering library [18].

Specialised controller blocks (current, speed and position)

These blocks contain replaceable building blocks from the internal controller and filter packages. The selected subcomponents may also be parameterised via dedicated parameter records.

Parameters

baseController    user selectable internal controller blocks
filterNumerator    reference filter numerator
filterDenominator    reference filter denominator

Force-fight compensator parameters

baseController_BearingForce    user selectable internal controller block
baseController_SpeedLVDT    user selectable internal controller block
baseController_PositionLVDT    user selectable internal controller block

Auxiliary blocks

FilterSelectable

parameters are identical to those of Modelica.Blocks.Continuous.Filter

FilterTF (continuous)

filterNumerator    filter numerator
filterDenominator    filter denominator
initType    initialisation type of the derivative (choices: no initialisation, steady state, specified initial state, specified initial output)

x_start    initial state vector
y_start    initial output

FilterTF (discrete)

b    filter numerator
a    filter denominator
Ts    sample time
initFixed    false: initial state values are only guesses
true: state vectors are initialised by the specified values

\[ x_{\text{start}} \] initial state value vector

Park’s transformation
no parameterisation required

- Controller interfaces and respective attached components

**Basic controller blocks**

| 2 real inputs | reference signal |
| 1 real output | control signal to a connecting model |

**Specialised controllers (current, speed and position)**

| real input | reference signals |
| bus interface | all relevant signals collected into bus objects |
| real output | control signal |

**Force-fight compensator**

| 2 dedicated interface buses | measurement signals from motors |
| 1 real output | calculated force compensation |

- Expected numerical challenges

Models in this part of the library do not have considerable impact on simulation performance. Discrete-time controllers’ sampling and fault injections are the only sources that trigger events.
8. Conclusion

The major outputs of this deliverable D31.1 are:

- Description of the EMA simulation model library architecture and implementation conventions
- Detailed specification of the library model components

This document is and will be used directly during the EMA model library implementation. The next steps are the implementation and validation of the model library. This task is split between the WP 3.1 partners according to the WP 3.1 description of work. At the time of writing, a first version of the model library is already available.
References

[18] F. van der Linden, General fault triggering architecture to trigger model faults in Modelica using a standardized blockset. 10th International Modelica Conference, Lund, Sweden, March 10-12 2014