# COUPLING MECHANICAL AND THERMAL LUMPED PARAMETERS MODELS FOR THE PRELIMINARY DESIGN OF POWER TRANSMISSIONS DRIVEN BY THERMAL ISSUES

**Emeline Faugère*, Jean-Charles Maré**, Christophe Changenet***, Fabrice Ville****, David Delloue ***
***MESSIER-BUGATTI-DOWTY, Vélizy, France**
****Université de Toulouse, INSA-UPS, Institut Clément Ader, France**
*****Université de Lyon, ECAM Lyon, laboratoire d'Energétique, France**
******Université de Lyon, INSA Lyon, LaMCoS, UMR CNRS 5259, France**
*emeline.faugere@ens-cachan.fr;mare@insa-toulouse.fr*
*christophe.changenet@ecam.fr;fabrice.ville@insa-lyon.fr*

## Abstract

*An innovating user-friendly tool has been developed to help designing mechanical transmissions with respect to thermal-mechanical issues. Based on a non-causal computation software, it allows an easy plugging-component approach. Innovation is also linked to the possibility of varying the refinement of each component of the gearbox.*

*It is thought to fit with the engineer top-down exigency: using the proposed model enables to take important decisions with respect to lubrication choice, cooling or architecture choices.*

*Eventually, it is to be completed with new libraries of components, and will communicate with other software to make the design of electromechanical actuators the more efficient as possible.*

## 1 General Introduction: Need for more detailed thermal analysis of mechanical power transmissions

Making mechanical power transmissions safer, cleaner and cheaper has become one of the main target for the design of new generation of power drives for embedded applications.

As actuated systems are part of its core business, MESSIER-BUGATTI-DOWTY wants to improve its knowledge and maturity on power transmissions thanks to enhanced modeling processes. This improvements, with application to airworthiness systems, are currently carried out within the frame of the European project CLEAN SKY.

Opposite to the conventional hydraulic solutions where the heat generated by the mechanical losses is naturally evacuated from the power users to the hydraulic tank, several electrical designs suffer from the thermal issue that is most of the time the key design driver fixing cost, mass and geometrical envelope. This is underlined by recent works on many electrical components for planes (i.e. flight controls, landing gears, thrust reverser, steering actuators…). A consequence of weight saving is that the power-bulk ratio increases more and more and leads to a reduction in heat dissipation capacity.

Moreover, in electrically actuated solutions, using high speed-low torque motors is generally the best solution to minimize mass but it requires speed reducers to meet the high load/low speed actuation needs at load level. As a consequence, in most of embedded actuators applications, electro-mechanical actuators (EMA) solutions are preferred to pure electrical actuation.

Unfortunately, temperature effects play a major role in the actuator sizing process where the heat generated by the mechanical reducer (especially friction phenomena) and the electrical motor (copper and iron losses) are to be quantified with care, as a function of the operating environment (radiative sources and convection with ambient). This task is to be performed at any time of the mission to get representative values (e.g. max, mean or RMS temperatures) to support early design solutions selection.

The proposed communication deals with the development of a simulation process and associated tools and libraries to enable the designer in addressing simultaneously power transmission and heat transfer in mechanical reducers/actuators. The preliminary design process involves a set of lumped parametric reducer components which are combined to form the whole reducer to be simulated within the Dymola-Modelica environment. However, the method could be applied to any non causal simulation software.

## 1.1 Specifications and expected advantages of the proposed approach

The model was developed to meet the following design specifications:

- The actuator model should be easily created as an assembly of generic components.
- Each component is associated with a set of models having progressive degree of complexity (i.e. from one to several thermal nodes). Different refinement models components can be plugged together.
- For frictions losses, the models can be chosen among different level of complexity, depending on the known coefficients and/or the admissible simulation load. The model structure enables implementing any available knowledge model.
- The model has validation purpose and help features in order to analyze and make decision. E.g for friction reduction or optimizing the way to dissipate the heat generated by power losses.

Most of the design of mechanical power transmission is generally seen as mechanical problems (performances, efficiency, dynamics, vibrations…) and solved as well. It is quite rare to find modeling and simulation facilities dealing with thermal issues in mechanical transmission at system level.

The proposed modeling approach and the associated component libraries provide a new way to address the design of thermally constrained actuation systems.

For this reason, the proposed model aims at:

- Representing accurately the mechanical losses from analytic friction models that are all based on scientific literature (see section 2.4)
- Representing separately or jointly the mechanical and thermal issues. This coupling is detailed in the followings.

Putting the effort on the development of non causal models enables either analyzing a given design from a direct simulation of the model or addressing the inverse problem by propagating the power demand from the load to the motor. It also enables an easy plug of generic components without causality restrictions (i.e. plugging two inertia or capacities together)

This can be easily illustrated considering the assessment of heat exchange between the housing and the ambient in order to define a cooling solution. A similarly approach can be used to define teeth's surface coating knowing the maximal admissible temperature at the surface contact, or to predict the required exchange surface knowing the power loss to dissipate.

## 1.2 State of the art

### *1.2.1 Modeling physical phenomena*

Although several software allow multi-physics modeling, and most of them allow thermal coupling with other phenomena (i.e. fluids mechanics, electromagnetism …), few of them proposes to couple friction losses in gearbox with its thermal behaviour. Friction losses in gearbox elements seem to be too specific to be addressed by a general simulation software.

Though, literature is abundant on those issues:

- Friction between pinion and wheel teeth: Henriot [1], Velex [2], Buckhingham [3]

- Friction in rolling elements bearings: SKF [4], Harris [5]
- Churning losses in case of a splash lubricated gearbox: Bonnes [6], Changenet [7], Terekhov [8]

### *1.2.2 Components approach*

From an other point of view, some software like Matlab-Simulink [9] or AMESim [10] propose a plugging-component approach, but their resolution schemes are natively causal.

On its side, the Dymola-Modelica [11] software also uses a plugging-component approach but enables non-causal modeling which allows direct ore inverse simulation, according to the known inputs. This facility has driven the selection of the environment for the development of the following models.

Dymola already proposes mechanical libraries including friction losses models for gearbox components (e.g. bearing friction or lossy gear). However, these models only address the mechanical point of view and with a rough modeling of the friction phenomenon. This status has emphasized the need to develop and implement advanced thermal-mechanical models based on the following proposed approach.

### *1.2.3 Thermal modeling*

The interest in thermal modeling issue having grown up for the last 20 years, it is quite new and thus still under development.

To end with the state of art, three scales of thermal modeling currently exist:

- <u>A macroscopic modeling</u> is proposed by the ISO standard [12] where the entire gearbox is assumed to be isothermal. Although this approach is of interest for the preliminary design, it becomes rapidly irrelevant when one aims to know how the heat is propagated into the gear box.
- <u>In the nodal modelling</u>, the model is a network of resistive and capacitive lumped elements, based on an electrical analogy. This approach is mostly developed in research laboratories and is not widely deployed in industrial tools. [13-17]
- <u>Although finite elements</u> studies on teeth or bearings have often been conducted, it appears impossible to do so on an entire gearbox level mainly because of the huge computation load it requires. In addition, this distributed parameters modeling approach is not consistent with the development of system level models.
- <u>Coupling different scales of modelling</u>: Manin [16] coupled a nodal gearbox with a finite elements carter. However, it does not seem to be really efficient. [14, 15].

## 2 Proposal of a generic thermal mechanic approach

The main issues for the thermal simulation of mechanical reducers come from the need for realistic modeling.

In the proposed approach, the mechanical reducer is decomposed into basic components such as bearings, pinions, shafts, housing, seals, etc... This way, the thermomechanical model is defined by associating the basic components according to the reducer topological architecture and the selected materials.

The process to make the virtual gearbox from the real one will be here illustrated with the FZG test rig [18] (Fig 1)

As a requirement, the numerical model should be built as the real gear box is: two shafts, each one holding a gear and being linked to the housing with two rolling bearings which make a pivot joint.

Fig.1 scheme displays the structure of a single stage spur gear reducer with splash lubrication and plane-parallel shape housing. The reducer model is built combining the shafts models that are connected to the rolling bearings models, the pinion or wheel models and the housing model.

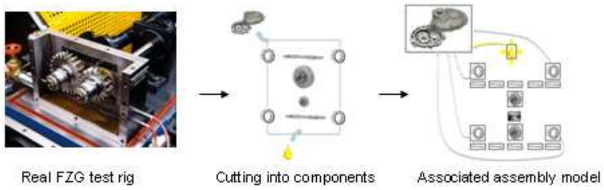


Fig. 1 .Example of the FZG cutting in generic elements

As a consequence, the proposed tool develops libraries of generic bearings, shafts and gears (Fig.2).

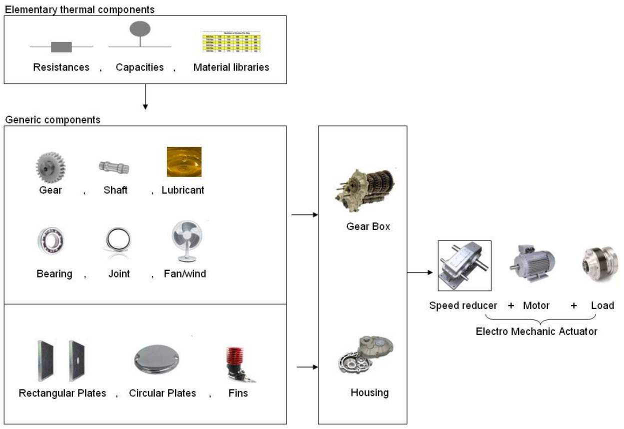


Fig2 . Getting created an EMA.

To respect the expected modularity, each shaft is cut in pieces to fit bearings and gears width as in-between elements width too (see Fig 1c). Oil has also to be taken into account as a component itself.

To finish, as the gearbox, the housing should be described as a particular assembly made as far as possible of generic components (plates, perforated plates, cylinders…).

## 2.1 Tool box constitution : a library of generic components to connect to create a specific gear box

All sub models are made from a specifically designed library to be used within the Dymola/Modelica simulation environment.

Once generic components created, the user will only combine them to create specific gearbox, housing, motors… so that the model of a full specific electromechanical actuator (EMA) is modelled.

Introducing in a user-friendly way these complex couplings is the heart of the proposed modelling process in which the engineer only inputs the torque/speed/ambiance time history of the mission profile once the reducer is modelled, just like running a virtual experiment.

## 2.2 Thermal and mechanical network, superposition and coupling

In this section will be discussed how mechanical and thermal networks are implemented, and then coupled. This will be illustrated with the inner model of the 'gear' generic element.

### *2.2.1 Method to create networks*

Different networks must allow the generic elements plugging. This way, elements are given connectors, transmitting flow and/or potential variables.

For thermal issues, the connector will communicate heat flow and temperature information, for mechanical (functional rotational) network, the variables exchanged are torque and angular velocity. We will see in section 2.2.4 that in some case (to deal with interfaces models), it is compulsory to create interfaces connectors that exchange specific geometry values.

### *2.2.2 Thermal behaviour modelling under mechanical losses*

From the thermal point of view, the internal model structure of each basic component is developed from nodal networks of lumped nodes involving resistive and capacitive effects.

The gear 'most detailed' model goes from the contact surface to shaft (node A) to the teeth node (node B) (in the nodal lumped approach, all teeth are at the same temperature, thus only one node is necessary to represent them).

The following figure zooms on generic wheel thermal-mechanical networks that integrates equations computing conduction and oil/wheel convection resistances with respect to choices of materials, type of oil, geometry, evolving temperature and mechanical operating conditions.

Conduction heat transfer is represented by thermal resistances, as convection transfer is (convective resistances mostly depending on fluid flow velocity). Convection is the case of oil projection (convection between oil in between teeth and teeth node), and convection between the gear flanks and oil or air intern fluid. The thermal flux source feeding this network is to be the dissipated power by friction in churning phenomena.

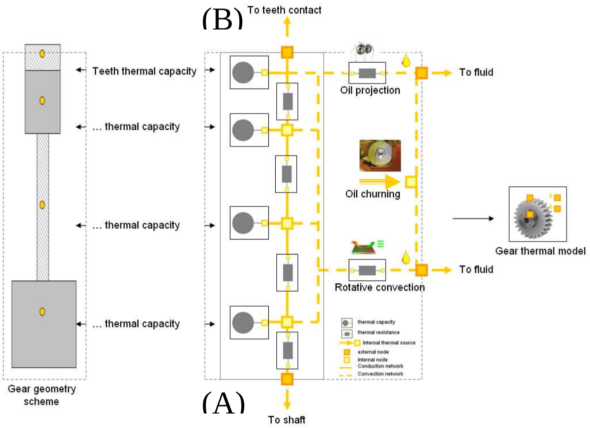


Fig3 Thermal network of a generic gear component

### 2.2.3 *Mechanical power transmission behaviour modelling*

The mechanical network is build on the ability to model the fourth quadrants behaviour.

This model is not aimed to represent dynamic rotational behaviour; hence it can be improved to do so, using the same methodology as described in this paper.

Mechanical loss is seen as dissipated power. In this precise gear modelling case, it becomes a resistant torque on the gear.

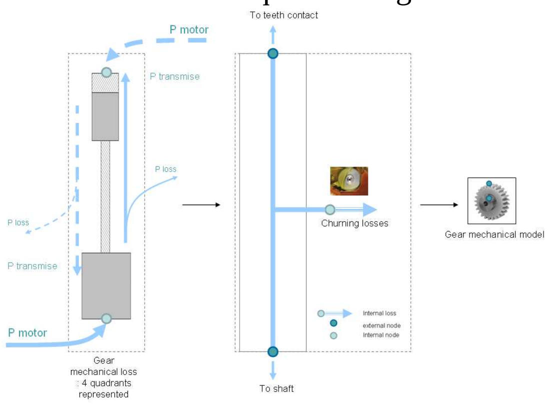


Fig4 Mechanical network of a generic gear component

Besides rotational mechanics transmission, forces repartition is needed for some particular calculation (i.e. rolling bearings losses). A global fundamental principle of dynamics has to be written to feed those models. This could be automatically done when using multi-body libraries.

### 2.2.4 *thermo-mechanical coupling*

The coupling between mechanics and thermal is illustrated in the following scheme (Fig.5) that highlights the links between mechanical losses and heat sources, as well as the major contributors to their dependence on the actual local temperature.

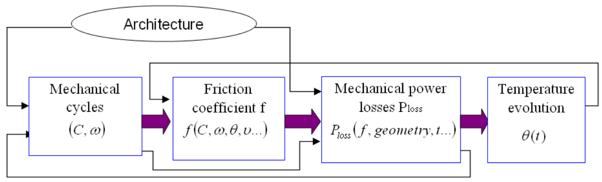


Fig5 : coupling thermal and mechanics

Fig. 5 illustrates this coupling on the gear generic component example (red arrows).

The principle couldn't be simpler: mechanical losses are directly linked to thermal flux sources (kinematic energies created by fluid movements are neglected in case of splash lubrication). The thermomechanical loop is closed by the fact that the thermal network calculates temperatures level that influences oil properties, thus the calculus of mechanical losses. This is illustrated in Fig. 6

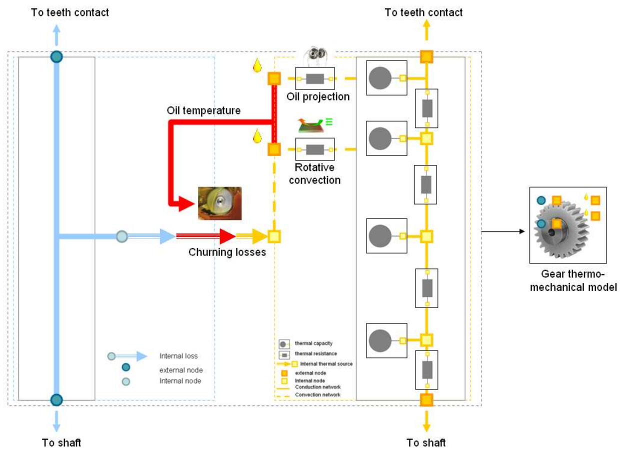


Fig6 Coupling thermo-mechanical on the generic gear model example

### 2.2.5 *Interfaces management*

To deal with interfaces issues, special blocks have been developed to represent the wheel/pinion interface where striction resistances [19-20] and friction losses are calculated with the knowledge of both wheel and pinion geometry. That explains the need in geometry interfaces connectors (triangle connectors).

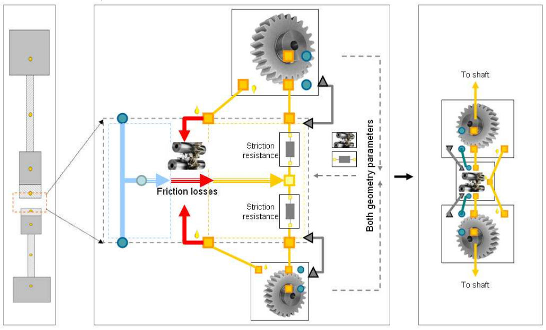


Fig7 Modelling interfaces

Eventually, this figure (Fig 7) combines all the connectors a generic model can encounter:

- Thermal connectors
- Mechanical connectors
- Geometry connectors for interfaces

## 2.3 Levels in modeling components and physical phenomena

The proposed design tool enables different structure levels that are associated with different losses modelling levels (e.g. the designer can implement a friction loss chose to be constant or calculated on more complicated models like the Velex' equation).

It can make the simulation faster if no precision is necessary. Moreover, as it often happens that a designer doesn't possess all the parameters to implement a complex model, it is useful to access simulation even with preliminary models.

In that way, pre-sizing studies can progressively be detailed, starting with a very few number of parameters. This approach is consistent with the upcoming integration of the Dymola simulation software within the Catia V6 platform that will enable linking top level models and 3D models in a bi-directional way, in a product data management way. Developing the thermal level modelling that can be associated with the mechanical power transmission level enables the designer to address hardly coupled effects through multi-domain (and later multi-scale) simulation.

### 2.3.1 *Thermo mechanical structure refinement levels*

To answer the designer specifications to model components with more or less refinement, the

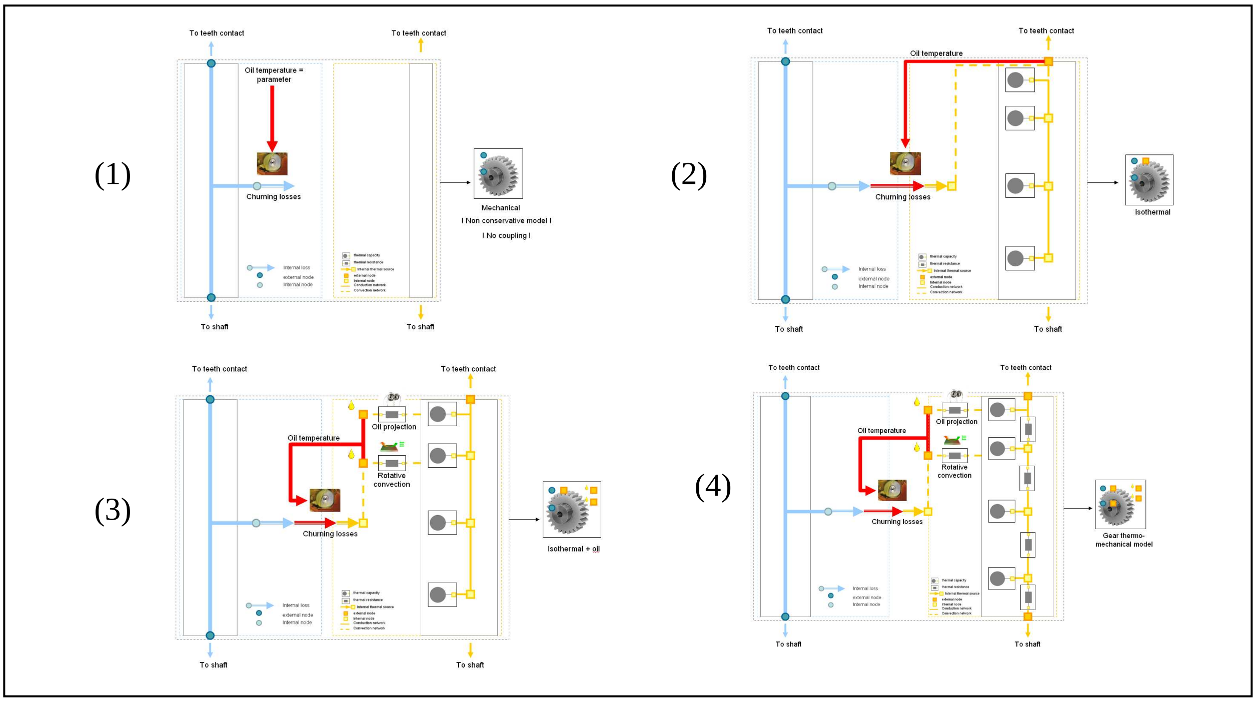


Fig8 Structure levels in modelling a gear

presented tool proposes four levels of structures to model a component. This is illustrated on Fig. 8 with the gear generic model example.

- (1) A basic non coupled model where only mechanical is represented. In this model, friction losses are calculated knowing oil temperature as a parameter. It is important to note that this model is not power conservative whereas thermomechanical ones are.
- (2) Isothermal: A first step to thermomechanical model, where oil and metal have the same temperature, governing oil properties taken to calculate losses. In this model, no conduction is considered, but capacities are, i.e. thermal dynamics is represented.
- (3) Isothermal + oil: A second level of thermomechanical model, that is quite the same as the previous one, except the fact that oil is not considered at the same temperature of the metal. Consequently, convections models have to be implemented.
- (4) High level model: this model is the same as the previous one adding conduction phenomena, i.e. modeling temperature gradient from teeth node (B) to shaft node (A).

### *2.3.2 Refinement in losses models.*

The target is to enable designing a gearbox, and run a thermomechanical model even if the designer lacks parameters to implement a complex analytical model.

To follow the previous gear-contact example, the model will have i levels to model churning losses and j levels to model friction losses, which are themselves calculated from the knowledge of the normal forces to contact (Fn), the friction coefficient (fo), etc… themselves having k choices of refinement levels.

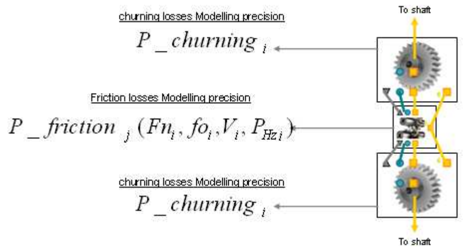


Fig9 Losses model levels

Here are proposed 5 levels of refinement as an example to model gear contact losses:

- No loss = ideal component
- Given dissipated power
- Given efficiency
- Analytical formula
- Integral calculations (or Finite Elements)

## 2.4 Modelling the heat generated in mechanical power transmissions

This paragraph presents the generic form of equations used in the tool to represent high level models.

All these effect are strongly dependant on the instant operating conditions like temperature or velocity and load. This particularity is developed in paragraph 3.

### *2.4.1 Heat sources*

- teeth contact [1], [2]

$$P_{contact} = fo.\Lambda_{contact}.P_{drive} \qquad (1)$$

- churning with splash lubrication (fluid shear) [6-8]

$$P_{churning} = \Lambda_{ch}.Cm.\omega_{gear}^{\ 3} \qquad (2)$$

- rolling bearing friction [4-5]

$$P_{bearings} = (Mo + M1).\omega_{bearings} \qquad (3)$$

In this tool, particular efforts have been made on how important are the hypothesis hidden behind those equations

### *2.4.2 Heat transfers*

- solid/lubricant or solid/ambient fluid (air) [7], [13], [21]

$$h = \frac{Nu.\lambda}{L} \qquad (4)$$

$$Nu = a.Gr^{b}.\Pr^{c}.\mathrm{Re}^{d} \qquad (5)$$

# 3 Example of application: virtual thermal mechanical model of an embedded Electro Mechanical Actuator (EMA)

## 3.1 Description of the gear box

Previously was described how to create a specific gear box thermomechanical model. In this paragraph, an embedded EMA model is proposed, made of 4 shafts and 3 gear ratios (see fig 10). Let's imagine the engineer identified a thermal critical default on the second stage and wants to model with care its behaviour. Moreover tests having shown that 1st and 3rd stages don't need that much precision, the designer choses to model them with low structure refinement level. With the help of the friendly modular model, he will first create the gearbox, then command load and rotational speed. Fig 10 presents a possible assembly for this application:

- structure refinement :2nd stage gears are of high level (red), 1st and 3rd stage gears are 'isothermal models + oil' (orange), the 1st shaft is 'isothermal'(green) and the 4th shaft doesn't model any thermal behavior (blue).
- Friction loss modeling refinement : around the focus zone, 2nd stage gears, contact and rolling bearings are 'high' modeled (double line), then other losses calculations are made with basic levels models (thin line)

## 3.2 Boundary conditions: duty cycles and external conditions (T, wind…)

Prior to run the simulation, the designer must input the mission profile as torque, speed, environment temperature time histories and the eventual air velocity around the carter.
All results are non dimensionalized with start values and 1000 to 2500 seconds of a given longer duty cycle.

### *3.2.1 Duty cycle (Torque, velocity)*

Torque is imposed at the 4th shaft (load), and angular velocity at 1st shaft (motor drive).

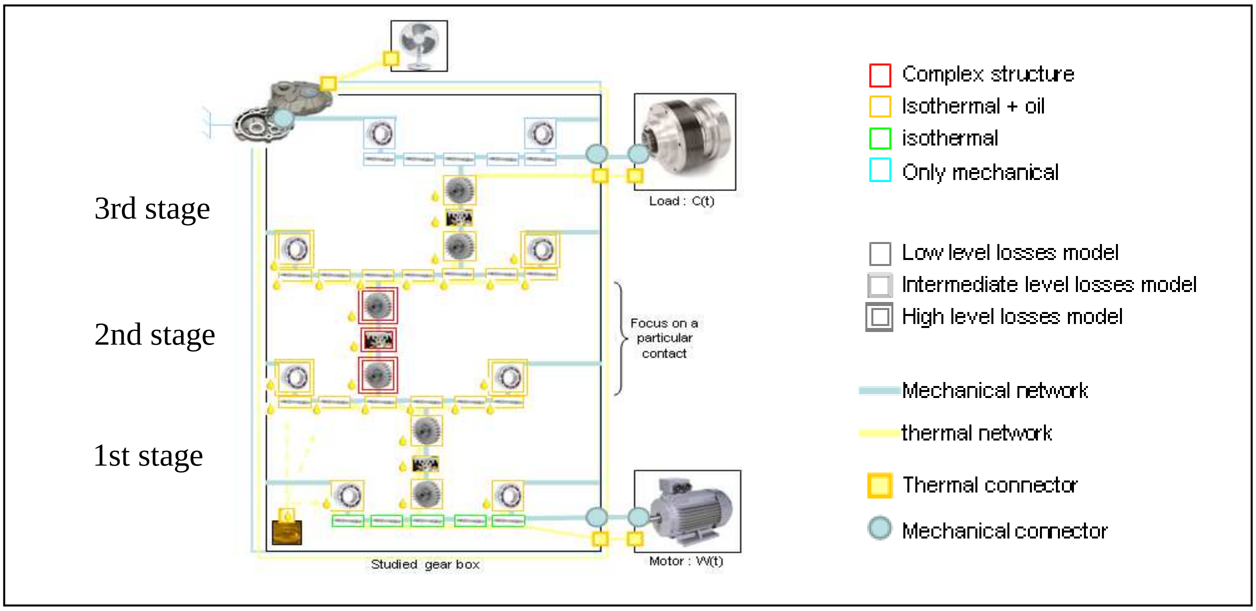


Fig10 example of application

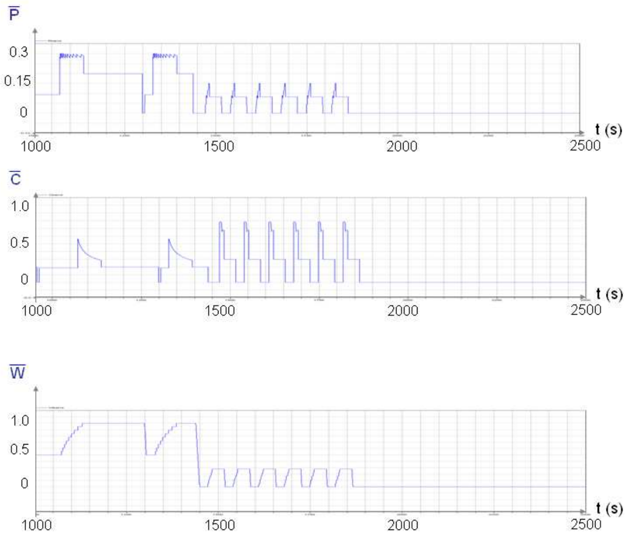


Fig 11 : load, velocity and transmitted power

### 3.2.2 *Boundary conditions*

As the EMA flights with the plane (embedded specifications), outside temperature is aimed to vary significantly as well as convection conditions blowing on the carter (plane velocity + wind)), and radiative boundaries.

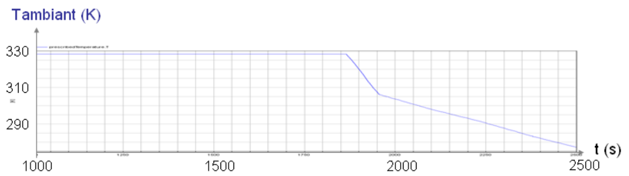


Fig12. : Ambient temperature conditions

## 3.3 Simulation results

### 3.3.1 *Temperature variations*

The following figures plot the simulated temperatures on the following nodal points of the thermal network: 2nd stage contact temperature, and gear nodes.

Those curves could be used for the pre-validation of the reducer architecture; the principles selected for lubrication and cooling as well as surface coating (with respect to friction and thermal exchange), surface temperature and still other design parameters…

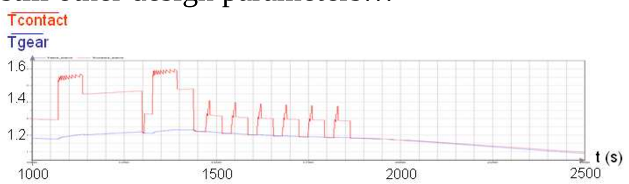


Fig13 contact and gear temperature

### *3.3.2 Losses and efficiency*

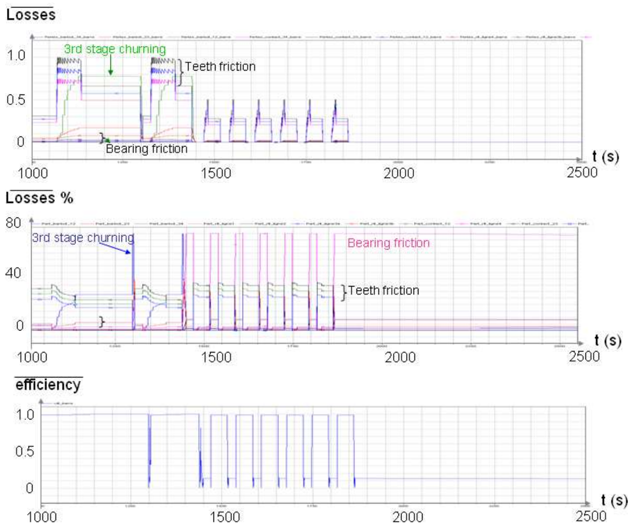


Fig 14 : losses and efficiency

For particular operating conditions, churning losses can become higher than friction ones. In this application, since rolling bearings are small, their losses remain small too.

### 3.3.3 *Coupling oil properties variations and mechanical cycle*

Fluid properties varying with oil temperature: focus on the coupling effects of the model.

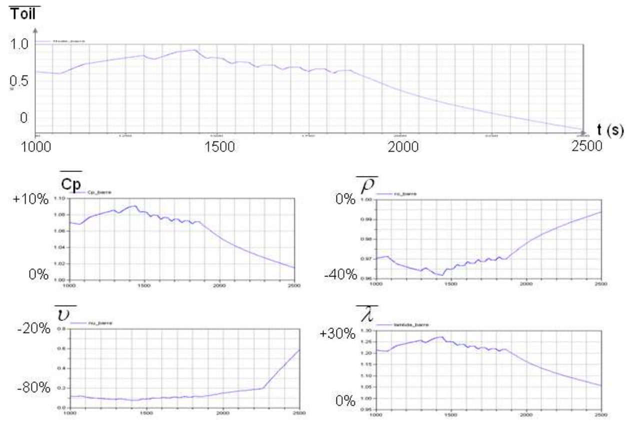


Fig 15 : Oil properties variations (T, t)

### 3.3.4 *Losses coupling*

Churning losses influence contact losses since they decrease the normal transmitted force, then, the contact losses.

It can appear then important to calculate normal forces with respect to all losses, not from basic models.

## 4 Conclusion

This innovating user-friendly tool aims to change the approach of preliminary mechanical transmissions design with respect to thermal-mechanical issues.

Indeed, it is thought and built to fit with the engineer top-down exigency that is to find the optimal actuator from a given torque/speed cycle playing on the as large as possible panel of parameters of the model (e.g. material, shape, lubrication…).

Using the proposed model enables to take important decisions with respect to lubrication choice, cooling or architecture choices.

Eventually, the tool herein presented is to be completed with new libraries of components, and will communicate with other software to make the design of electromechanical actuators the more efficient as possible.

## Notations

$\Lambda_{contact}$ : geometry parameter
$fo$ : friction coefficient at teeth contact
$P_{drive}$ : driving power
$\Lambda_{ch}$ : geometrical and fluid flow parameter
$Cm$ : friction torque
$\omega_{gear}$ : angular velocity of the gear.
$Mo$ : friction torque, independent on load
$M1$ : friction torque depending on load
$\omega_{bearings}$ : angular velocity of bearings.
Gr : Grashoff number
Pr : Prandtl number
Re : Reynolds number
h : exchange convection coefficient
Nu : Nusselt number
L : flow characteristic length
$\lambda$ : fluid thermal conductivity
a,b,c,d : flow coefficients.

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