EMRP IND13 REG D1.5 (D4.1.5)

Good Practice Guide on “Thermal modelling of precision engineering equipment.”

1. Focus of Guideline

This guideline is written for stakeholders that are concerned with or plan to model or investigate the thermal behaviour of complex precision engineering equipment. It aims to provide information of advantages and disadvantages of some modelling approaches. It gives hints for choosing the suiting approach and shows their limits of application and precision of their results. The guideline contains a comprehension of the results which were given in the EMRP IND13 WP4 project reports (D4.1.2-D4.1.4/ REG D1.2-D1.4).

2. Complex Modelling

The term “complex modelling” is used in this guideline and all other investigations and reports in the context of JRP-IND13 when a 2D or 3D geometrical model is estimated, which uses local discretisation, segmentation and approximate solutions of boundary value problems instead of a large scale (analytical) description for thermal calculations. For complex modelling mostly Finite-Element-Methods (FEM) or Finite-Differences-Method (FDM) are used.

Independent from the chosen mathematical method, the general aim of complex modelling is to investigate the thermal behaviour of the object of investigation (the precision engineering equipment), to calculate temperature fields, heat flow distributions and to estimate temperature sensitive components. In this context, the properties which are described in the following sections are typical for most of the complex modelling tasks in modelling precision engineering equipment.

2.1. Requirements

The quality of the estimated complex model and the precision of the results strongly depend on the quality of the knowledge about the input parameters, which are mainly **geometry**, **heat transport mechanisms** at the object of investigation and **thermal properties** of the used materials. Thus, before starting the modelling one needs to find out if sufficient trustable information is available to enable accurate calculations and to estimate the expected error-level. The following list with typical contributions and questions will help to find this:

General

- Are transient or static calculations needed?
- Are coupled simulations (mechanical-thermal / electrical-thermal) needed?
- Which software should I use or is available?
- What are the features of this software – are they sufficient?
- What error level is sought? Can it be achieved regarding the answers of the above questions?
- Do I have limitations from hardware (CPU, RAM) or software (limitations due to licenses or in number of degrees of freedom (DOF))?

Geometry

- Are the dimensions of the components/ parts known?
- Is the construction very complex or exist parts with big aspect ratios which lead to high element/ node numbers (high computational effort)?
- Can there be make geometrical simplifications on geometry without affecting the correctness of the results?
- Are a partition and a modelling of components instead of modelling the whole equipment possible?

- Do geometrical symmetries exist which allow a reduction of the model dimension (3D to 2D)?

Heat transport mechanisms

- Which heat transport mechanisms take place and are they relevant?
    - Heat conduction
    - Convection
    - Radiation
- How do joints between parts influence the thermal coupling?
- Can the thermal contact between parts be modelled?
- Which tools are provided by the software to model the heat transport mechanisms?
- Is it possible to estimate (theoretically or by measurements) the necessary boundary conditions?
- Are the material properties for estimation of the boundary conditions sufficiently known?
- What is the uncertainty of the estimation of the boundary conditions to be applied?

Material properties

- Are the thermal properties of the materials known?
    - Heat capacity $c_p(T,t)$
    - Density $\rho(T,t)$
    - Thermal conductivity $k(T,t)$
    - Spectral emissivitty $\varepsilon(T,t,\lambda)$
    - Enthalpy $H(T,t)$ – if phase changes need to be regarded
- Is there a time dependency of the quantities that needs to be regarded for transient simulations?
- Are the material parameters temperature dependent?
- What is the uncertainty of the material parameters?
- How do other influencing quantities, e.g. humidity or atmospheric pressure, change the model?

2.2. Advantages

The main advantage of complex modelling is the direct accessibility of temperature and heat flow values in the results. The evaluation of e.g. gradients and time-dependent changes can be done for surfaces, edges or cuts of parts and even components. Changes in the model can be realised easily and reactions on this can be evaluated quickly. Hence, complex modelling is a very convenient tool for parameter studies, preliminary calculations before a construction of equipment or optimisation of geometrical dimensions and materials.

2.3. Disadvantages

The setting up of a validated model of complex engineering equipment is a very time consuming process. Literature research for material properties, estimation of boundary conditions, implementation of the real world's behaviour into software (which has limitations), successive steps of model validation with accompanying measurements and also computational time make the modelling and calculation procedure lasting up to many month, depending on the level of difficulty of the problem.

The uncertainty of the calculation results follows roughly from a quadratic summation of the uncertainty contributions of all the input quantity listed in section 2.1. Hence, it seldom reaches values of 10% or less (10% deviation of the calculated temperature or heat flux values to actual values in reality). Even when no comparing measurements can be carried out or complex heat transfer takes place (convection and radiation problems) the deviation can reach 100% or more.

According to that complex modelling is not a suiting tool for the exact estimation of absolute temperature values. It cannot compensate carrying out measurements.

3. Reduced Modelling

Spatial discretization of the heat equation associated to its boundary conditions lead to complex models, with large number of degrees of freedom. These models are unsuitable for real-time control and inversion of experimental data. A model reproducing the behaviour of the system with a satisfying accuracy and smaller number of degrees of freedom should be defined.

Model reduction has attracted considerable attention, different methods have been developed. In the following the Modal Identification Method developed in Pprime institute is presented.

3.1. The Modal Identification Method

The identification of a reduced model through the MIM is done through the following steps:

- Define the structure of the reduced model able to describe the involved physics.
- Generate Input/output data (measured or simulated) representative of the system dynamics.
- Identify the parameters of the reduced model through the minimization of the quadratic residual between the previously generated data of the system and the outputs of the reduced model for the same input data.

3.2. Advantages:

- The reduced models are generally composed of a small number of equations which reduces considerably the computation time.
- When experimental data are used to build the reduced model, approximations specific to complex models (thermophysical parameters, boundary conditions, etc) are avoided.
- The reduced models can be used to achieve real-time control.
- Faster and less complex testing of control algorithms due to lower order of models

3.3. Disadvantages

- Reproducibility and uncertainty of results depends on the quality of the input data from measurements or simulation.
- Outputs of reduced models may be some heat fluxes. In such a case, heat flux data have to be obtained from simulation with a reference model (Complex model) or measured in-situ.

4. Comments

Additional information can be found in the following EMRP IND13 related publications:

1. Schalles, M. and R. Thewes, *Comparison of Thermal Modeling Approaches for Complex Measurement Equipment.* International Journal of Thermophysics, 2014: DOI 10.1007/s10765-014-1637-x.
2. Bouderbala, K., et al. *Model reduction and thermal control by predictive control of new cylindrical measurement apparatus*. in *TEMPMEKO 2013*. 2013. Funchal, Madeira.