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Object-Oriented Inverse Modelling of Multi-Domain Aircraft Equipment Systems with Modelica

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Abstract

This paper describes the use of Modelica for investigating the multi-physical power behaviour of aircraft equipment systems within the 5th European Community (EC) programme "Power Optimised Aircraft" (POA) [1]. It gives an overview of the object-oriented structuring of an aircraft systems library which is currently being developed for the physical modelling of conventional and future "more electric" aircraft systems. An inverse modelling approach is presented, which allows to analyse the non-propulsive power behaviour as a result of given load profiles for the electrical, mechanical, hydraulic and pneumatic equipment systems. In addition the paper describes the definition of assessment criteria, to evaluate and quantify the energy consumption of the aircraft equipment systems. The criteria, their implementation in Modelica and the results from an example are presented.

Keywords: *object-orientation, aircraft systems, multi-domain modelling, inverse modelling, system assessment, more electric aircraft*

1 Introduction

Multi-physical modelling is gaining a more and more important role within areas such as robotics, the automotive or aircraft industry. Particularly with respect to the complexity of aircraft systems, such as air conditioning, electric power generation, avionics, flight controls, in-flight entertainment etc., the method of multi-physical modelling allows to simulate all aircraft systems, which use different forms of power, in one integrated model. Different physical domains have to be considered in the simulation of complex aircraft systems. An example is presented in figure 1, which shows a diagram of the conventional power generation, distribution and use on a civil aircraft.

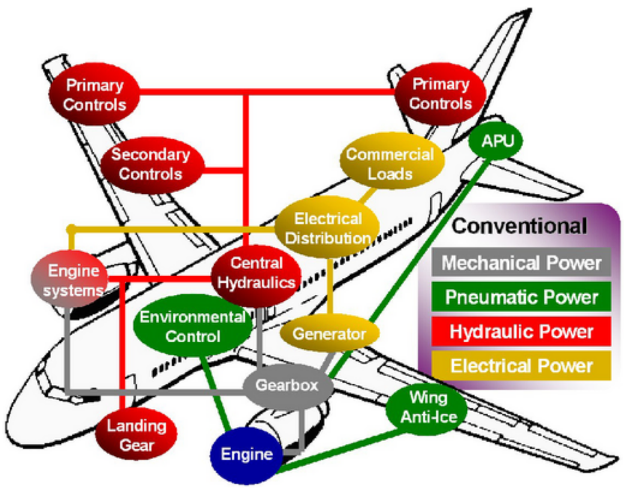

Figure 1: *Diagram of the conventional power distribution in a civil aircraft [2]*

Fuel is being converted into power by the engines of the aircraft. Most of this power is expended as propulsive power in order to move the aircraft. The remainder is converted into four forms of non-propulsive power, known as electrics, mechanics, hydraulics and pneumatics, which are necessary to operate the aircraft systems. On a conventional aircraft, a relatively large amount of the non-propulsive power extracted from the engines is lost, due to inefficient power conversion, transmission and consumption by the aircraft systems.

The European Aircraft Industry has identified the potential for improving the competitiveness of their

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products by advancing the development of more power efficient aircraft systems. A reduction in operation cost of the next generation – power optimised – aircraft is projected to be achieved by a reduction of the system power demands, leading to savings in fuel consumption. To promote the development of new technology and more power efficient aircraft systems, the EC has founded the POA project [1], involving European aircraft, equipment and engine manufacturers. Two of the goals established for the POA project are the following: a reduction of the non-propulsive power consumption and a reduction of the fuel consumption.

Within the POA project, the aircraft manufacturer defines the top-level system requirements and a set of so called ”feasible” system architectures. The engine and equipment manufacturers are responsible for developing advanced technology system components, such as generators, air conditioning packs and flight control actuators. Equipment hardware is being delivered to the so called Aircraft Systems Validation Rig (ASVR). By equipment testing on the ASVR, their performance is going to be validated while being operated simultaneously and connected to an aircraft-like electrical power supply. Whereas testing on the ASVR can represent just a cutout of a feasible systems architecture, the so called Virtual Iron Bird (VIB) offers the capability to analyse the entire aircraft architecture including all systems. Also, the VIB has the flexibility to investigate all sensible combinations of feasible system architectures. On the VIB, the aircraft systems are going to be represented by simulation models. The VIB uses component models, that are being delivered by the equipment manufacturers, to compose an integrated aircraft systems model. The models delivered to the VIB will be validated by stand-alone hardware testing done by the equipment manufacturers and by coupled hardware testing done on the ASVR. Using the validated component models, the VIB simulations can predict and compare the power consumption and behaviour of the various ”feasible” system architectures. The simulation of the systems power consumption and dynamic behaviour is one of the VIB’s contributions to the overall scope of the POA project. In addition, all the different system architectures are going to be optimised in a later step.

2 Object-Oriented Modelling Environment

The terms of reference within the current EC programme ”POA” comprise the development of a structured simulation environment enabling to assess the various aircraft system architectures. By means of ”Modelica”, this simulation environment is being realised as a ”Modelica Library”, whose structure is presented in figure 2.

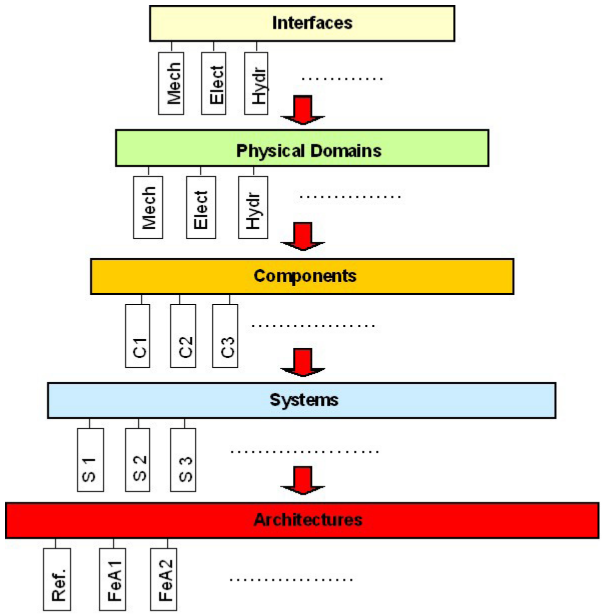

Figure 2: *Diagram of the hierarchically structured library*

Basically, the library consists of 5 levels, all of which being connected in a hierarchical manner. The sub-library, named ”Interfaces”, is the starting point of the entire library. It comprises several model connectors and is arranged according to the different domains, known as electrics, mechanics, hydraulics and pneumatics. The next higher level, that builds up on the sub-library ”Interfaces” is called ”Physical Domains”, and enables the generation of basic domain specific models. Within this hierarchically structured library, the two previously mentioned levels are used to model the components of aircraft systems, as well as to generate the aircraft systems themselves. All simulation models showing the aircraft systems or their components have laid down interface definitions, which for example enable the exchange of component models with distinctive features on a specific system level. On the uppermost level of the entire library different ”feasible architectures" can be generated and thus assessed according to the criteria of power consumption. However, this is dependent on the number and the diversity of the numerous aircraft system architectures. The structured and object-oriented organisation of the entire library enables the automatic combination of the system models towards different architecture models. Figure 3 shows an example of an aircraft model containing an electrical power generation system (EPGS) on system level. The EPGS has several components, one of them is the shown electrical generator.

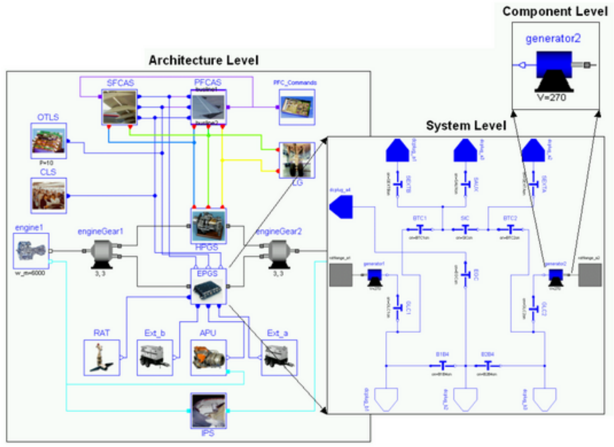

Figure 3: *Modelica diagram of a hierarchical aircraft model*

3 Inverse Modelling Approach

For the VIB aircraft system simulations an inverse rather than a direct modelling approach is used. An inverse model can be interpreted such that the meaning of the input and output functions is exchanged. The unknown variables of a direct model are treated as the known input functions of the inverse model, and the known variables of the direct model are treated as the unknown output functions of the inverse model.

Both modelling approaches are discussed in the following using a simple example with an electrical power source (engine and generator) and a control surface driven by an electromechanical actuator. For a given control surface load profile (torque and angular position) the basic VIB simulation task within the framework of the EC project POA is to compute the electrical power and the resulting change in fuel consumption.

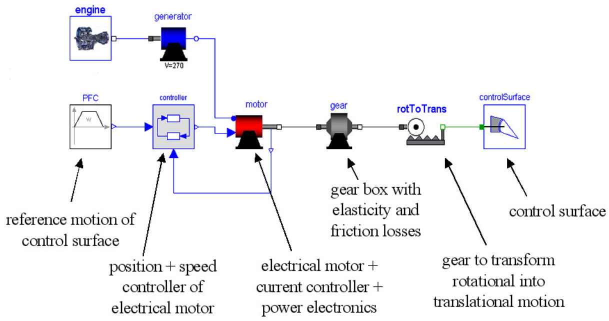

Figure 4: *Diagram of a direct electro-mechanical actuator model*

Figure 4 shows the direct model for the above example. The generator, driven by the engine, supplies the motor of the electro-mechanical actuator with electrical DC power. The voltage level of the generator is determined by means of the generator control unit, which is not shown in the figure 4. The motor is steered by a motor control unit and changes, via a gearbox, the position of the control surface according to the demanded values. In this example, the motor control unit commands by means of the demanded position, the necessary motor current to move the control surface under the predefined load.

For the comparison between the direct and the inverse modelling approach, only the part of the electromechanical actuator and the control surface model in figure 4 is considered. The simulation model of the electrical power source (engine and generator) is still the same for both modelling approaches. The generator model and the engine model are used in these two applications, to calculate the necessary electrical power and the resulting change in the fuel consumption.

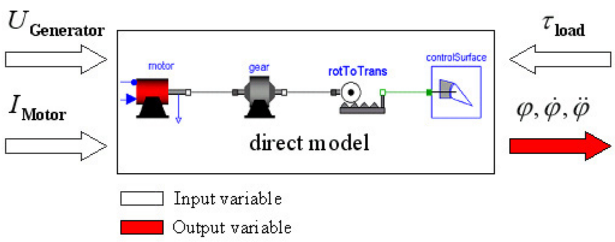

Figure 5: *Diagram of the inputs and outputs variables of the direct electro-mechanical actuator model, shown as a black box*

Focusing on the electromechanical actuator (motor and gearboxes) and control surface model (figure 4), the input variables for the direct simulation are the motor current I_{Motor} (derived from the demanded and actual position by means of the motor controller), the generator voltage $U_{Generator}$ (impressed at the actuator motor) and the acting load τ_{Load} at the control surface (see figure 5). The unknown variable in this case is the real motion $\varphi, \dot{\varphi}, \ddot{\varphi}$ of the control surface, which will be calculated according to the given load profile. On the basis of this direct actuator model, the necessary electrical power can be computed by means of the actual actuator motor current I_{Motor} and its corresponding actuator motor voltage U_{Motor}. The actuator motor voltage U_{Motor} is an internal model variable and therefore not shown in the diagram of the inputs and outputs variables of the direct electro-mechanical actuator model in figure 5. By means of the two actuator motor variables, the necessary electrical power on the generator voltage level $U_{Generator}$ and the change in fuel consumption can be finally calculated with the generator and engine models.

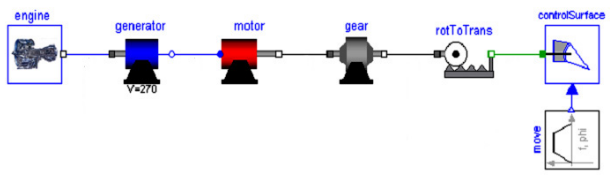

Figure 6: *Diagram of an inverse electro-mechanical actuator model*

Figure 6 presents an inverse model in contrary to the direct model shown in figure 4. Based on the inverse modelling definition, the meaning of input and output of the direct model is exchanged. For the inverse electromechanical actuator and surface model, the input variables are the predefined motion φ and load τ_{Load} found at the control surface and the generator voltage $U_{Generator}$, impressed at the actuator motor. The output variable (unknown variable) for the inverse model is the motor current I_{Motor}. Comparing the direct actuator model (figure 5) and the inverse actuator model (figure 7), the meaning of inverse and direct interpretation is well visible. The resulting necessary power of the generator and engine can be calculated in the same manner as for the direct model.

In Dymola, the DAE (differential-algebraic equation system) corresponding to the inverse model is being handled with the same methods like the DAE of any other (direct) model. The methods applied by Dymola are the Pantelides algorithm and the dummy derivative method. Since the Pantelides algorithm will differentiate equations, the known input functions may also be differentiated, which leads to the well known effect that the derivatives of the input functions must

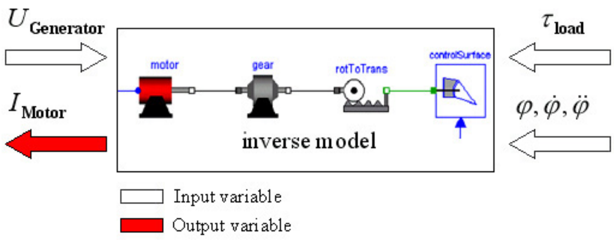

Figure 7: *Diagram of the inputs and outputs variables of the inverse electro-mechanical actuator model, shown as a black box*

exist up to a certain order [3].

In the present example in figure 7, it is imperative that the input signal φ is at least twice continuously differentiable to compute the required signal derivations $\dot{\varphi}, \ddot{\varphi}$ within the simulation models. To ensure that the model input signal is differentiable, the measured signal is treated by filter or spline-interpolation in this case.

Due to the fact that in Modelica the models are described in an object-oriented and physical manner, an inverse model is almost identical to the corresponding direct model. As the only significant difference, the inverse model does not require any representation of the controller structure that exists in the real system or component, whereas the direct model generally comprises the controller structure for calculation of the motor current I_{Motor} as a function of actual and demanded motor position. Due to the unavoidable control error and physical effects in the drivetrain (elasticity, friction) the actual control surface position is different from the predefined control surface position φ. This error induces errors in the resulting power consumption, which depend on the controller accuracy and the drivetrain effects.

In contrast to the direct model the inverse model matches per definition exactly the predefined load profile (τ_{Load}, φ) and therefore correctly describes the power consumption. A further advantage of the inverse modelling approach is the lower model complexity due to the absence of possibly complicated and proprietary controllers from partner companies.

For the above mentioned reasons an inverse modelling approach is used as a general concept for all of the electrical, hydraulic, mechanical and pneumatic power consumers. For each of the consumers, predefined load profiles during a typical flight profile are available to drive a multi-domain inverse model for simultaneous computation of the mechanical and pneumatic power take-off from the engines.

4 Power criteria

Among others, the goals of the POA project are the evaluation and optimisation of the power demands in future aircraft architectures. To measure and assess the quality of an architecture some criteria are needed which quantify the energy consumption, the peak power, the weight, etc. Predefined flight profiles (movement of surfaces, landing gear, state of the air-conditioning system) yield the power characteristics of the different physical domains such as hydraulics, electrics, mechanics and pneumatics from the architecture simulations. In the following the definitions of the criteria, which are related to the dynamic simulations, their implementation in Modelica and the results from an example are presented.

To evaluate the overall energy consumption during a flight profile, it is suitable to define the average power

$$P_{Average} := \frac{1}{t_e - t_0} \int_{t_0}^{t_e} P(t)\,\mathrm{d}t$$

with the current power $P(t)$ at the time t, the start time t_0 and the terminal time t_e. $P_{Average}$ describes, which integral averaged power is required for the operated manoeuvre in the timeframe $[t_0, t_e]$.

Beside the demand of average power there is also an interest on peak power which is relevant to the design of the aircraft components and systems. In a first step it is natural to define the peak power as

$$\max_{t \in [t_0, t_e]} P(t).$$

However arbitrary short peaks can unmeantly increase the value of the peak power, because only peaks holding a certain minimum duration T are of interest for evaluation. One approach for computing such a peak power could be sampling in combination with an algorithm for minimum power computation within a moving interval of length T. But this solution can be numerically very sensitive in respect of changes of initial values, parameters and the sampling time.

In order to achieve an appropriate solution, it can be helpful to define the peak power

$$P_{Peak} := \max_{t \in [t_0 + T, t_e]} P_{Filtered}(t)$$

for a fixed $T \in (0, t_e - t_0]$. $P_{Filtered}$ denotes a filtered power characteristic determined from the original power P. The "continuously moving average" filter computes for every time point t the integral average of the power P over a moving time window with the length T:

$$P_{Filtered}(t) := \frac{1}{T} \int_{t-T}^{t} P(\tau)\,\mathrm{d}\tau \quad (t \in [t_0 + T, t_e]).$$

Choosing $T = t_e - t_0$ yields as a special case the average power, and the equation $P_{Average} = P_{Peak}$ holds. In this sense the peak power can be considered as a generalisation of the average power.

For implementation of the power criteria it is advantageous to define the energy function $E(t) := \int_{t_0}^{t} P(\tau)\,\mathrm{d}\tau$. The differential equation `der(E) = P;` with the initial equation `E = 0;` determines the energy E in an unique way. Accordingly the criteria can be rewritten in terms of energy as

$$P_{Average} = \frac{E(t_e)}{t_e - t_0} \quad \text{and} \quad P_{Filtered}(t) = \frac{E(t) - E(t-T)}{T}.$$

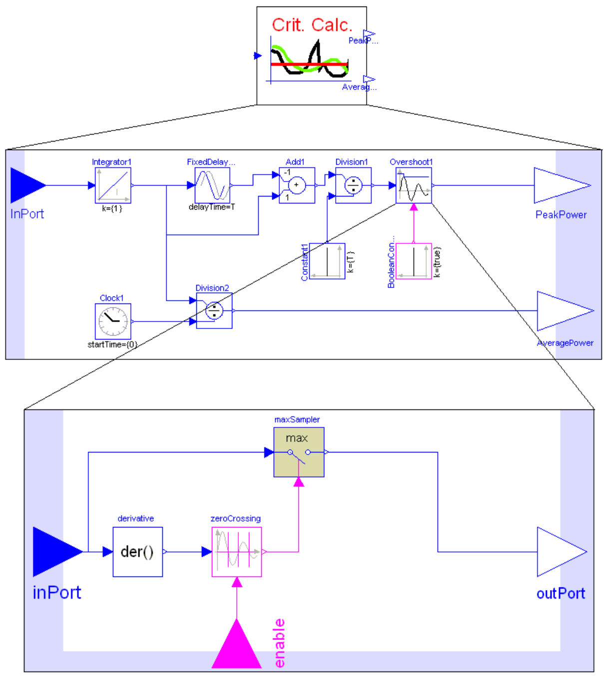

Figure 8: *Modelica model for the criteria average and peak power*

In figure 8 a Modelica model for the criteria is shown in the block "Crit. Cal.". The necessary time delayed evaluation $E(t-T)$ and its derivative $P(t-T)$ are realised in the block "FixedDelaywithDerivative". It remains to find the maximum of $P_{Filtered}(t)$. The general problem is to compute

$$\max_{t \in [t_0, t_e]} |u(t)|$$

for a time depending variable u. The Modelica solution with indicator functions is implemented in the block ”Overshoot1” in figure 8.

```
block ZeroCrossing "Trigger zero crossing of input signal"
  extends Modelica.Blocks.Interfaces.BooleanBlockIcon;
  parameter Boolean includeInitialEvent=false
    "= true, if start time shall be included as event";
  parameter Boolean includeTerminalEvent=false
    "= true, if terminal time shall be included as event";
  a;
  Modelica.Blocks.Interfaces.InPort inPort(final n=1)
    "Input signal"
    a;
  Modelica.Blocks.Interfaces.BooleanOutPort outPort(final n=1,
          signal(fixed=true)) "Output signal" a;
  Modelica.Blocks.Interfaces.BooleanInPort enable(final n=1)
    "enables the block" a;
protected
  Boolean enabled(fixed=true) = enable.signal[1];
  Boolean disabled(fixed=false) = not enable.signal[1];
  Boolean u_pos(fixed=false) = enabled and inPort.signal[1] > 0;
equation
  outPort.signal[1] = (change(u_pos) and not initial()
     and not edge(enabled) and not edge(disabled))
     or (initial() and includeInitialEvent)
     or (terminal() and includeTerminalEvent);
end ZeroCrossing;
```

Figure 9: *Modelica model for zeroCrossing*

To determine the maximum of $|u|$ the block ”zeroCrossing” in figure 8 creates a state event in the case that the derivative $\dot{u}$ changes its sign (see figure 9 for the Modelica source code). The appearance of the state events is passed on as a boolean to ”maxSampler” (= ”triggeredMax” from ModelicaAdditions library). There the respective values of $|u|$ are compared and the greatest one is selected as u_{max}. In addition the values $|u(t_0)|$ and $|u(t_e)|$ can be selected for possible candidates of maximal values of $|u|$ by setting the parameter includeInitialEvent, includeTerminalEvent in block ”zeroCrossing” in figure 9.

Due to the fact that all the time points t with $\dot{u}(t) = 0$ are defined by state events, these points and the respective values of u are computed very accurately by root finding.

Possible problems, like described for the sampling method, should be avoided by the introduced approach with filtering and determining the exact maximum of $P_{Filtered}$. It is remarkable on the shown definition and implementation of the criterion peak power, that maxima are computed with the help of derivatives, but no derivative of the power P is needed.

To demonstrate the criteria the example from chapter 3 is considered once again. Only the motor and the two gears are combined to one model ”ElectricActuator” (see figure 10). The evaluation of the criteria are exemplified by the mechanical power at the engine shaft. Therefore, in figure 10 the additional model ”Criteria” is inserted between ”Engine” and ”DCGenerator”. In this model the mechanical power is measured by a rotational power sensor and transferred to the criteria calculation block (see figure 8 for details) as an input signal.

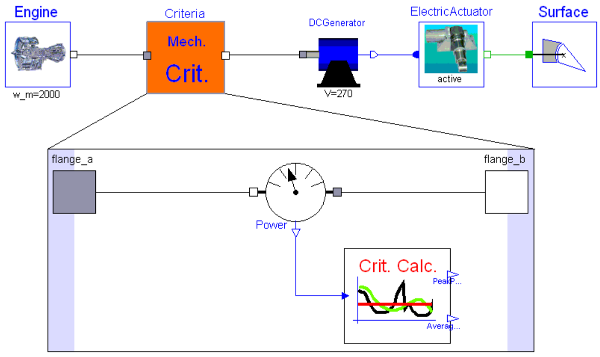

Figure 10: *Model example for criteria evaluation*

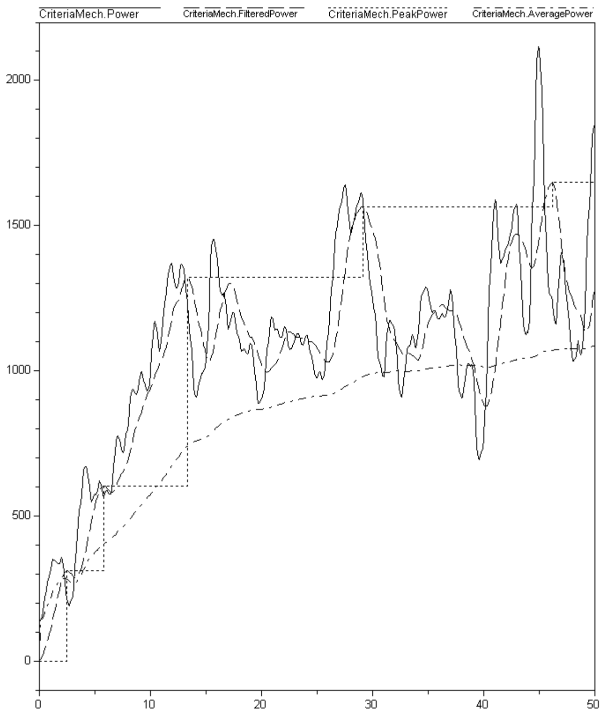

Figure 11: *Simulation results of the above example in figure 10*

For the overall simulation measured data for load torque and moving angles from a flight profile are loaded inside the model ”Surface”. The resulting power characteristics at the engine shaft are shown for 50 s in figure 11 with $T = 2\ s$. Beside the both criteria – average power and peak power – the power P and the filtered power $P_{Filtered}$ are plotted as well. Please notice, that intermediate values of peak power do in general not correspond to the peak power up to the intermediate time, but only for $t = t_e$.

5 Conclusion

Within the framework of the European project ”Power Optimised Aircraft” (POA), the ”Virtual Iron Bird” (VIB) serves as an analysis and simulation tool to predict the behaviour and non-propulsive power demands caused by the systems installed on a large civil aircraft.

The VIB is set up as a hierarchically structured Modelica library, containing five different levels. To build up this modelling library, tailored and validated component models are being used, which are provided by the equipment manufacturers involved in the POA project.

Rather than a direct modelling approach, an inverse modelling approach is used for the aircraft system simulations on the VIB. The selected inverse approach has been described in this paper by an elementary modelling example.

In order to evaluate and later on to optimise the future aircraft architectures according to the POA project goals, certain assessment criteria are set up in Modelica for the VIB. The assessment criteria allow to quantify the different aircraft systems, which is discussed in this paper by an elementary example.

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