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Complementary approximate modeling in Matlab and Modelica

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Summary

Multi-disciplinary analysis of coupled systems of multiple physical nature requires effective representation of the system components and their interfaces. The modeling language Modelica is designed for integrated modeling of multi-disciplinary coupled systems, which may be defined qualitatively by the underlying physical relations, or quantitatively by data sets. This paper presents a software tool (MultiFit) developed in Matlab, which provides facilities to efficiently analyze and approximate such data sets. The resulting approximation functions quantitatively represent the system behavior and can be exported directly to Modelica source code. As an illustration the application of this tool in an aircraft power system integration study is presented.

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1 Introduction

Multi-disciplinary analysis of coupled systems of multiple physical nature requires effective representation of the system components and their interfaces. This in order to allow for direct integrated modeling of such systems, for example consisting of coupled electric, mechanic and hydraulic components, as commonly found in the aerospace engineering practice. The object oriented modeling language Modelica (Modelica Association, 2002) provides a comprehensive framework for physics-based modeling of such systems. Modelica system models are hierarchically defined and can be built up from interconnected (standard) component models (Otter & Olsson, 2002). The interconnections among component models are achieved by specific Modelica connector objects, in which generic relations between components are defined. Component models, such as resistors, springs and pumps are collected and maintained in Modelica component libraries, which are made available (freely or commercially) to other users, thus contributing to an efficient way of working. The physical basis of a standard component's behavior is implemented in the component's model-object by the qualitative representation of the physical relations. For example, a standard electric resistance is implemented by the qualitative relation between voltage and current: V=I*R. However, what is still required to complete the component model definition is the quantification of the component's behavior, i.e. the quantitative specification of the physical relations of the component model (e.g., the value of R in the simple example of the electric resistor). For simple components the quantification can be easily achieved by specification of one or a few parameter values. But components with far more complex behavior, as commonly found in aerospace engineering practice, generally require non-linear relations for which the quantification is often not at all trivial. The Modelica modeling language is well suited for implementing the component’s behavior by physical relations but less adequate for quantification of these relations if these are represented by multi-dimensional data sets of measured or computed data. This paper presents an approach to deal with the quantification of such component models in Modelica, in particular when based on computed data sets from external dedicated simulation programs. As an illustration of the complementary approximate modeling capabilities offered by Matlab (Mathworks, 2004) and Modelica we present a case study in which an integrated model of power supply and consumption aboard civil aircraft is created and evaluated.

2 Approximation methods

The quantitative specification of component models in Modelica can be considered as the determination of the quantitative relations between two or more variables of the component model. In the case of the resistor model mentioned above, for example, that would be the value of R for a linear resistor, or the relation between the resistance and current, R=f(I), in the non-linear case. Any insight or knowledge of these relations that is available should be used in this specification, for example for the non-linear resistor it might be known that the relation between the resistance and current is of a linear, quadratic, or higher order form. In (Sjöberg et al., 2002) for example, an advanced method for system identification by parameter estimation of such relations using a Modelica interface to Mathematica is presented. In some cases however, such knowledge is not directly available as a mathematical expression but as a data set (or table) with samples (measured or computed) of this relation. If such a data set of samples of the relation is available, there are several methods for interpolation, approximation and fitting to retrieve a mathematical expression that adequately represents the data set. Least squares fits of polynomial functions are well known, but not always the most suitable method. Other methods, such as methods based on splines, kriging models (Simpson et al., 2001) and neural networks, may provide better fits of the data set. These methods are however not always easy to use and the assessment of the quality of the fits with the different methods may be cumbersome. Therefore it is profitable to have good facilities to easily, accurately and efficiently analyze, represent and approximate the data, using a variety of both standard and state of the art methods. This functionality has been incorporated in a software tool for generic approximation, named MultiFit, that was developed at NLR in Matlab. Moreover this tool provides a direct interface to the Modelica modeling language by automatically exporting the approximation model to Modelica source code, and has been used in previous design and optimization studies, e.g. (Vankan et al., 2003).

3 The MultiFit approximation tool

In order to collect and streamline some of the readily available functionality for approximation, a number of approximation methods has been integrated in a Matlab based software tool. This tool, named MultiFit and developed at NLR, provides a coherent and intuitive graphical user interface (GUI) to a variety of approximation methods based on polynomial functions, splines, neural networks, radial basis functions and kriging models (Lophaven, 2002). Furthermore the MultiFit tool is equipped with facilities for inspection and analysis of the data sets and for automatic export of the approximate models to Modelica code. The functionality of this tool is very briefly illustrated in Figure 1 below. On the left the MultiFit GUI window for data selection and inspection is shown. In the left hand side of this window the user can divide the considered data set into separate data sets for the approximation (fitting) and for the assessment of approximation errors (verification). The graph in the right hand side of this window shows a plot of the selected fitting and verification data sets projected in a plane spanned by dependent and independent variables that can be selected from pull down menus by the user. It should be noted that data sets of any dimension can be approximated, i.e. $y=f(\mathbf{x})$ where a scalar ($y\in\mathbb{R}$) is fitted as a continuous function (f) of an arbitrary number (n) of independent variables ($\mathbf{x}\in\mathbb{R}^n$) to the considered data. In the right of Figure 1 the MultiFit main window is shown, where in the left hand side of the window the user can select and control the approximation method to be applied. On the right the quality of different fits to the considered data set can be compared and assessed. In the presented graphs, a comparison of the RMSE values of 2nd and 3rd order polynomial fits and a kriging model approximation of a data set is shown. Also shown in this MultiFit main window, is the File-pull down menu, from which a resulting approximation model can be directly exported to a Modelica source code file.

A more elaborate description of the functionality of the MultiFit tool, and in particular of certain aspects of the export to Modelica, is given in (Lammen et al, 2003).

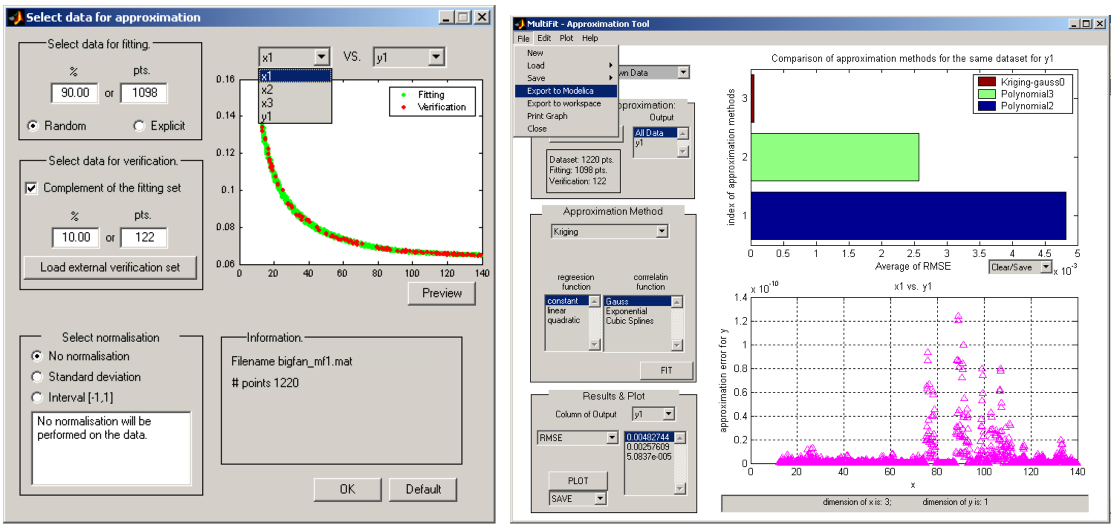

Figure 1. Illustration of the main functionality of the MultiFit tool

4 Integrated model of aircraft power supply system

4.1 Context

Power supply and consumption aboard modern aircraft involves a large variety of systems that have to operate in a wide range of conditions. Globally there are (groups of) systems of electric (e.g. generators, cabin equipment, avionics), mechanic (e.g. engine shafts, gearboxes), pneumatic (e.g. air-conditioning, which is part of the environment control system (ECS), wing ice protection system (WIPS)) and hydraulic (e.g. flight control system (FCS)) nature, and of combinations thereof. The operational conditions of these systems vary, for example, between very different atmospheric conditions, as found at altitudes from 0 to 12 km, or between very different values for velocity (e.g. 0-250 m/s), engine thrust (e.g. 0-200 kN) and payload or number of passengers (e.g. 0-300). In order to investigate the operational behavior of these systems under many different conditions, it is important to have integrated models in which the different systems are incorporated. The POA project (POA, 2002), in which an investigation is currently ongoing into the optimization of non-propulsive power consumption in civil aircraft, is therefore developing an integrated aircraft level system model, the so-called "Virtual Iron Bird" (VIB). Because of the multi-physical nature of the considered system models, the Modelica modeling language is used as the basis for the integrated aircraft level system model of this POA VIB (Bals et al, 2003).

4.2 Description

The case study presents an investigation of the power consumption of some of the non-propulsive equipment aboard an aircraft during a short phase under cruise-flight conditions (12 km altitude, Mach 0.82, constant engine thrust of 50 kN.). In order to briefly present the essence of the presented approach, we have limited the complexity of this study by considering only some of the major systems involved in the aircraft power supply and consumption and by considering only relatively simple models of these systems. The considered equipment are the pneumatic ECS, which is powered by so-called "bleed air" that is directly taken from the engine, and the electric systems "In Flight Entertainment" (IFE) and galleys, both powered via an electric generator. In addition the re-circulation fan of the ECS is considered, which is responsible for cabin air re-circulation and is driven by an electric motor. The electric system is modeled as DC for simplicity. It should be noted that by far most engine power (>90%) is consumed for propulsion. Nevertheless a significant amount of power (>100 kW per engine for average, say 200 passengers, civil aircraft) is consumed for non-propulsive purposes. Also it should be noted that only the equipment belonging to one of the two engines is considered in this study.

4.3 Qualitative model

In order to provide the engine power to the electric consumers, the (rotational) “mechanic” power of the engine shaft is converted via a gearbox and a generator, which are also included in the integrated model. To connect the consumers to the engine, appropriate physical connector objects as provided by Modelica are used. The global structure of this integrated model can be relatively easily integrated into Modelica, and is shown in the Modelica based modeling and simulation environment Dymola (Dynasim, 2004) in Figure 2. This model can be considered as a qualitative model because the quantitative behavior of the systems has not been implemented yet. In order to execute the integrated model, the system models must be quantified and simulation parameters must be defined.

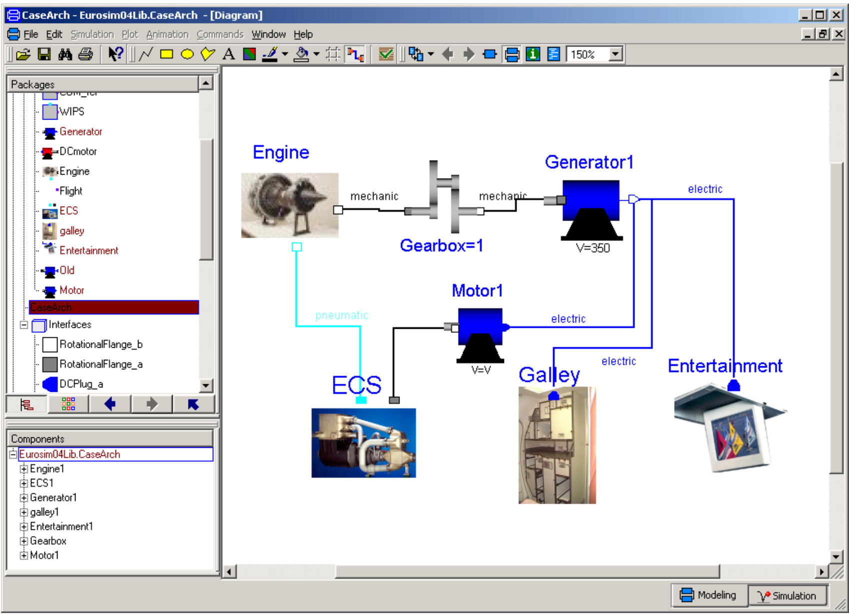

Figure 2. Dymola window showing the aircraft level integrated system model in Modelica

4.4 Quantitative model

The quantification of the IFE model is simply achieved by assuming a constant electric power consumption of 10 kW when turned on. The galley power consumption is assumed to be linear with its electric current and has a maximum power of 50 kW. The electric generator and motor are simply implemented as linear components both with an efficiency of 0.9. For simplicity a gear ratio of 1.0 has been used for the gearbox model. The ECS and engine models, however, are less trivial to quantify because of the complexity of their behavior. Therefore the behavior of these systems is first evaluated by dedicated simulation tools. A Simulink (Matlab, 2004) model of the ECS has been used, which was developed in the ASICA project (Kanakis & Hofman, 2001). This model predicts the mechanic power, in terms of rotation speed and torque, that is required by the ECS re-circulation fan. The input for this model consists of several quantities, such as atmospheric conditions and bleed air mass flow entering the ECS, which can be controlled by the pilot. An engine model developed in the dedicated Gas-turbine Simulation Program (GSP) (Visser & Broomhead, 2000) has been used. This model, which is based on one of the engine models from the GSP standard library, predicts (among others) thrust force and shaft speed as a function of fuel inflow.

4.5 Approximation

These engine and ECS models have both been executed in series of transient simulations, each converging into steady state conditions that are relevant for the analyses that are intended with the integrated aircraft level system model in this case study. The results of the simulations in these steady state conditions are collected in data sets that represent the behavior of these systems as required for the integrated system model. For the ECS this data set represents the re-circulation fan shaft torque as a function of ECS bleed air inflow, simulated during steady state cruise flight. For the engine this data set represents the thrust force as a function of fuel inflow and of bleed air and secondary shaft off-takes, also simulated during steady state cruise flight. These data sets are then post-processed in MultiFit, where the most adequate approximation functions to these data sets are determined. See for example Figure 1, where the engine model data set is shown, which was found to be best represented by a kriging model approximation. It should be noted that from the generated engine data set the approximation function was determined of the engine fuel consumption as a function of thrust force and bleed and shaft off-takes, which in fact represents an inverse of the original relation as predicted by the GSP engine model.

4.6 Integration

The approximation functions of the engine and ECS data sets were exported as Modelica source code and as such directly incorporated into the integrated system model in Dymola (Figure 2), where these approximation functions represent the internal relations between the different connectors of the engine and ECS model objects, respectively.

4.7 Simulation and results

The completed integrated aircraft level system model was applied in a system simulation during cruise flight, in order to evaluate the aircraft level response to certain pilot interventions. Some results of this simulation are shown in Figure 3 below. The scenario behind this simulation is hypothetical and is described in the following. All the values used are indicative for one half of the average civil aircraft that is considered (i.e. only one of the two engines, generators, galleys, ECSs, etc.). Initially the ECS is active and consumes 0.5 kg/s bleed air mass flow, and the galley and IFE are both active and consume 50 kW and 10 kW electric power, respectively. At a certain point in the simulation the temperature in the cabin is assumed to have risen above a certain threshold and the pilot increases the ECS activity, which is illustrated by the increase of the ECS bleed air mass flow starting at T=10 s (upper left plot of Figure 3). The ECS model (based on the ECS data set) predicts an increase of power consumption by the re-circulation fan due to this increase of ECS bleed air mass flow. The response of electric power consumption of the motor driving the re-circulation fan is visible in the upper right plot of Figure 3. Then around T=18 s the gradually increasing electric power demand at the generator reaches the maximum power capacity of the generator (100 kW), as a result of which the power that is available for the galley starts to decrease (upper right plot of Figure 3). Then at T=25 s the pilot switches off the IFE, which again makes available some electric power from the generator, which is then instantly consumed by the galley (see Figure 3). In addition to these responses of the electrical systems, also the response of the engine model is predicted by the integrated model. This is shown by the engine's thrust-specific fuel consumption (TSFC) in the lower right plot of Figure 3, which is affected by both the bleed air off take by the ECS and the mechanic shaft off take by the generator.

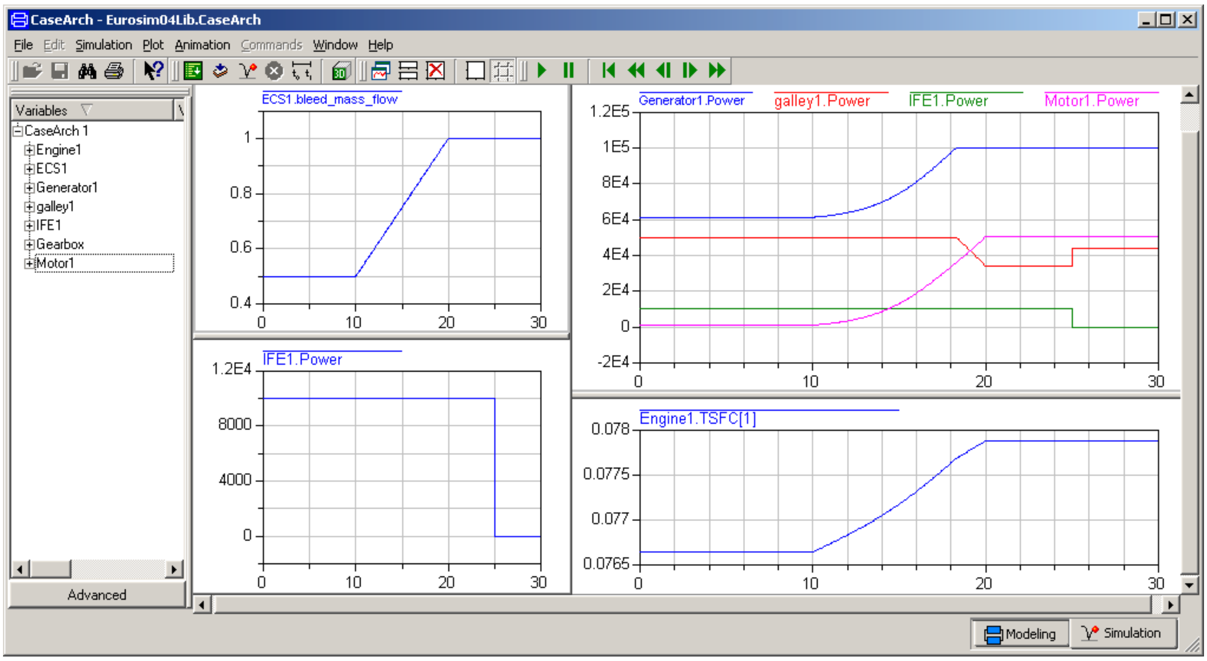

Figure 3. Plots of the interventions (left) and responses (right) in the use case simulation

5 Discussion and conclusions

A methodology has been presented for simulation of coupled systems of multiple physical nature based on approximate modeling, and has been demonstrated in a study of aircraft systems' power consumption. Although this study is strongly simplified and uses only global, indicative values for the systems' power consumption, it does illustrate how approximate component models can be incorporated in a Modelica system model and can be applied in an integrated system simulation. It is also demonstrated by the engine model implementation that this approach allows for easy inversion of original component model. The approximate component models have been quantified on the basis of data coming from dedicated simulation programs. For the other components standard Modelica component models have been used where possible, which have been parametrically quantified. A simple analysis has been shown of the interaction of only a few systems aboard an aircraft. A comparable investigation but far more complete and detailed is currently ongoing in the POA project.

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