ENHANCING THE DYNAMIC SYSTEM SIMULATION OF AN AIRCRAFT CABIN CLIMATE FOR COMFORT-IMPROVED CLIMATE CONTROL USING 1D/3D COUPLING

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Abstract

In cooperation with the Airbus Deutschland GmbH the Hamburg University of Technology (TUHH) participates in the German national funded project KATO (TP07 "Komfortverbesserte Klimaregelung"). One of the goals of this project is to model the inside of an Airbus A340 fuselage using dynamic system simulation in such a way that it can serve as a control path for advanced controller design. A model library is currently under development using the modeling language Modelica™. This library can be used for the setup of simulation models, that describe the thermo-pneumatic conditions in the pressurized fuselage. An adequate simulation model including heat flux, mass flow and momentum balance will be provided, which will serve as a control path, both for the computer-assisted controller development and for "hardware in the loop" applications. The Modelica™ simulation environment (Dymola™ [4]) used for this task offers the possibility, to export models through an interface to the software Matlab/Simulink™ [12]. Here they can provide a basis for controller optimization tools, e.g. MOPS [9], or can be integrated into control loops. By using this method, new temperature control techniques and control concepts can be tested quickly and economically.

1 INTRODUCTION

In the past of aircraft construction engineering activities focused especially on the solution of numerous technical problems, which mainly had the goal to optimize the flight performance, e.g. by improving of the airplane aerodynamics and engine performance. Other activities concentrated on the enhancement of the mechanical structure and on other security relevant factors for the passengers and cabin crew. These days also the investigation of possible improvements of the passengers' comfort plays an important role. Apart from the seat comfort and the kind of available entertainment system, the health aspect due to air quality and cabin climate particularly on long-range flights is of great interest [2], [3], [14]. Besides the layout of the air conditioning facility, the choice of suitable temperature sensors and their positioning in the aircraft, it is decisive, with regard to the required thermal comfort specifications for a changing cabin layout, to achieve an optimum design of the temperature controllers.
While the question of positioning the sensors can be determined best by means of a CFD-program due to its higher spatial resolution, the application of a 3D-model, as a control path for the controller design, is hardly realizable considering the limited technical possibilities that we still have today. Here the limits are set in particular by the immense expenditure of time for model setup and simulation and the needed amount of computing

power to perform this task.
For those reasons a high performance system simulation tool [4] and the modeling language Modelica™, which is a product of the non-profit Modelica Association [13], were chosen to handle the TUHH part of the KATO project.

2 THE ENVIRONMENTAL CONTROL SYSTEM

The environmental control system (ECS) is of great importance in order to keep the cabin pressure at a constant level and to provide air conditioning to the passengers and crew during the flight. In this chapter the function of the ECS during normal mode of operation is explained. With the exception of the new bleed-less ECS concepts a standard ECS works as shown in Figure 1.

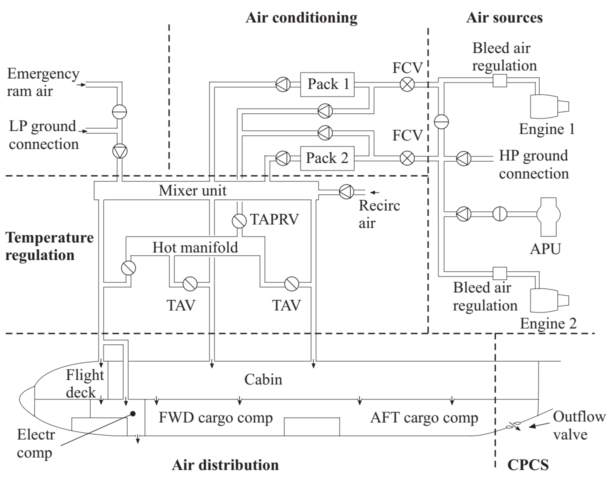

Fig. 1 *Scheme of a standard ECS with its subsystems [18]*

The bleed air (high pressure, high temperature) is taken from one of the compressor stages of the aircraft engines (*Air sources*). It then passes the flow control valves (*FCV*) and enters the air conditioning packs. One part of this air is led through air cycle machines (*Pack 1* and *Pack 2*), where it is expanded and cooled down. The other part is stored in the *Hot manifold*. In the *Mixer unit* the cooled air from the packs is mixed with filtered recirculation air coming from the cabin. The temperature in the *Mixer unit* is adjusted in such a way that it meets the lowest required zonal cabin temperature. Subsequently the mixed air is further distributed through the ducting to the cabin zones. Depending on the demand in the different temperature zones the fine adjustment of the air temperature is accomplished shortly after the *Mixer unit* by blowing in hot air through the trim air valves (*TAV*). The part of the supply air that is not reused as recirculation air leaves the aircraft through the (*Outflow valve*), which is responsible for the adjustment of the cabin pressure.

3 MODELING APPROACH

Thermodynamic systems in general consist of single units, e.g. fans, heater, cooler and volumes, that are connected to each other and are flown through by a working agent, such as water or air. Depending on the required level of detail the single components can be described through sets of algebraic, differential and/or partial differential equations.
For the modeling of an open thermodynamic system the most important elements are the control volume (CV) and the flow model. A control volume can be regarded as a continuously stirred tank. This means that there exists only one thermodynamic state in the CV and that every outgoing mass flow corresponds to this state. To connect adjacent CVs, a flow model is necessary that calculates the mass flow between the two due to a driving force, e.g. the pressure difference.

3.1 The Control Volume

The control volume approach used for this work is based on the staggered grid finite volume method described in [15]. It is commonly used for system modeling and one-dimensional discretisation. The thermodynamic model inside the CV contains the equations for mass and energy conservation for a system of constant volume:

$$\frac{dM}{dt} = \sum_{i=1}^{n} \dot{m}_{in,i} - \sum_{j=1}^{o} \dot{m}_{out,j} \qquad (1)$$

$$\frac{dU}{dt} = \sum_{i=1}^{n} \dot{H}_{in,i} - \sum_{j=1}^{o} \dot{H}_{out,j} + \dot{Q} + \dot{W}_s \qquad (2)$$

The calculation of thermodynamic states in the CV is realized by a coefficient database and a collection of functions for the thermodynamic behavior of air, which is already part of the *Modelica Standard Library* [13].

The fluxes on the border of the control volume are calculated by the half grid staggered flow model, which contains either a stationary pressure drop model or in case of a discretized control volume (pipe model) a dynamic momentum balance [17], [8]:

3.2 The Flow Model

The flow models used for this task are simplified pressure loss models. Right now there are three different variants possible: A constant laminar, a constant turbulent and a detailed friction pressure loss model.
While the first two models calculate the pressure loss by a constant linear or a constant quadratic dependency between pressure loss and mass flow rate, the detailed friction model is basically based on the equations that provide the basis for the *Moody Chart*. In order to avoid a division by zero in the laminar region at zero mass flow rate and to allow a flow reversal the equations of the detailed friction model have become mathematically rearranged [7].

4 THE SIMULATION MODEL

The simulation model basically consists of two major parts, for which experiments have shown that they have a significant influence on the cabin temperature behavior: the supply air distribution system (ducting) and the cabin itself.

4.1 The Ducting Model

The ducting system has a significant influence on the thermal behavior due to its large heat transfer area and its heat accumulation capacity. It mainly consists of insulated pipes made of glass-fiber reinforced plastic (*GRP*). The ducting is represented in the simulation model by a network of pipe models. Those models, in order to meet the behavior of real pipes (see Figures 2), where diffusion and friction effects lead to axial dispersion, are programmed as cascades of connected CVs.

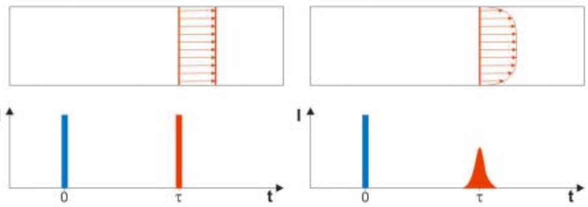

Fig. 2 *Dirac response of an ideal pipe vs. a real pipe*

The number of CVs of the pipe models is defined by the discretisation (N). Its influence on the behavior of the model can be seen in Figure 3.

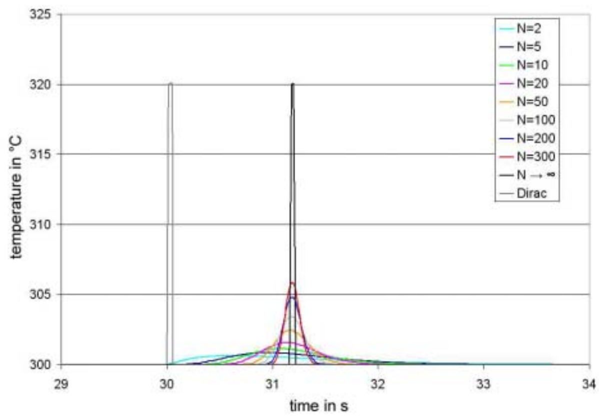

Fig. 3 *Dirac response of the pipe model in dependence of the discretisation N*

This technique derives from the domain of chemical engineering, where pipe reactors are modeled in a similar way.
Each of the CVs in the pipe model contains a dynamic heat transfer model [19], that enables the CV to calculate the heat transfer coefficient automatically, depending on the geometric pipe

data, the media properties and the flow velocity. Additionally the CVs contain two wall models, that calculate the heat conduction and the heat accumulation in the pipe wall and the insulation, and finally another heat transfer model to the surrounding ambient air.

4.2 The Cabin Model

Depending on the selected discretisation, the cabin model is represented by a more or less complex network of control volumes, that are connected via flow models. Contingent upon the arrangement of the volumes in the cabin, the CVs can contain heat sources (passengers, crew, electrical systems etc.) and heat accumulators (e.g. hat racks or seats). Figure 4 shows a generic CFD-Flow Pattern of an aircraft cabin and the corresponding 1D system simulation model.

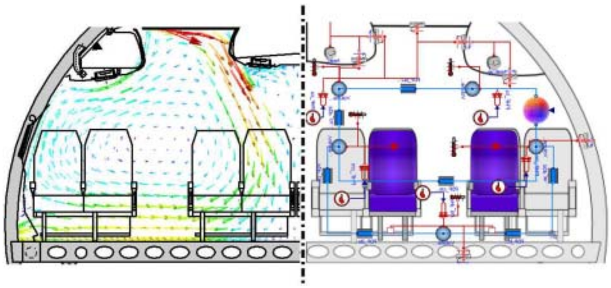

Fig. 4 *Generic scheme of the CFD air flow pattern in a cabin translated to a 1D simulation approach*

Fig. 5 *KATO test rig*

5 VALIDATION/SIMULATION RESULTS

First simulations of the cabin model, which neglected the influence of the ducting, showed that the results were not meeting the expected behavior measured in flight tests (see Figure 7). Therefore in addition to the comparison of the complex cabin models with the few available sets of flight test data a test rig was constructed (see Figure 5) for the validation and tuning of the simulation models.

With this test rig the acquisition of the necessary transient temperature data for the improvement of the system models could be obtained much more flexible and comfortable.
The test rig comprises of three cabin temperature zones, including the ducting. When compared to the scheme of the ECS (Figure 1) some analogies can be noticed. The mixer unit is represented by an air splitter. The task of the trim air valve is performed by an array of fast working heater units and the behavior of the ducting is replicated by insulated polypropylene pipes. The pipes in the test rig disembogue into six air inlets that are connected to the three independent temperature zones. The box shaped temperature zones are equipped with numerous electric bulbs that represent the additional heat load due to passengers, crew and electronic devices.
The experimental data from the test rigs ducting system showed a good correspondence with the simulation results obtained with the ducting model. Figure 6 shows the measured input temperature, the measured output temperature and the simulated output temperature of the test rig ducting model. The demand of the test rigs controller unit for this experiment was for a double input temperature step from 28 to 60 and from 60 to 70 degree Centigrade. The overshoot on the input temperature was caused by the controller unit triggering the heater units.
After the validation of the pipe model it was integrated into the cabin model. Afterwards a comparison of the simulation results with available flight test data showed a more realistic behavior of the cabin model temperature (see Figure 7).

Currently the test rig is further upgraded by the installation of a hot and cold air manifold, in order to be more flexible in generating temperature changes and to be able to meet the behavior of a real trim air system better, and a cabin contour, to better converge the cabin air flow pattern.

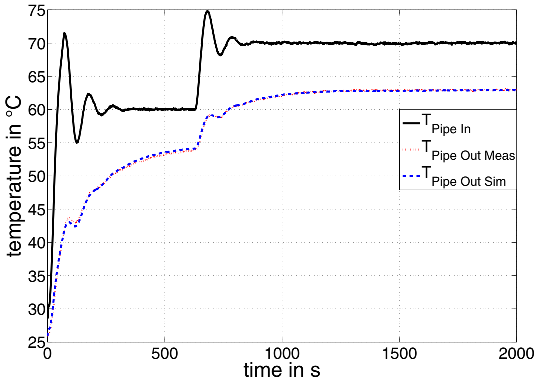

Fig. 6 *Simulation result of test rig ducting model*

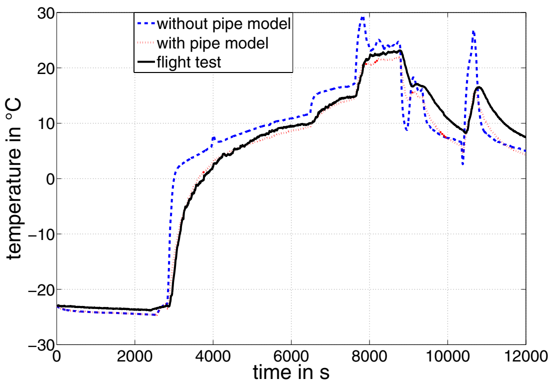

Fig. 7 *Simulation results for cabin zone model with ducting*

6 USING THE CABIN MODEL AS A CONTROL PATH

For the export of the Modelica™ simulation model Dymola™ offers an interface to Simulink™, the so called *Dymola Block*. Within this block the Modelica™ model can be chosen, compiled and edited. For a successful export to Simulink™ a simulation model has to be prepared in Dymola™ by dragging the necessary input and output values as signal connectors to main model layer. This procedure is required because otherwise the in- and output connectors won't be accessible in Simulink™. Figure 8 schematically shows the export procedure.

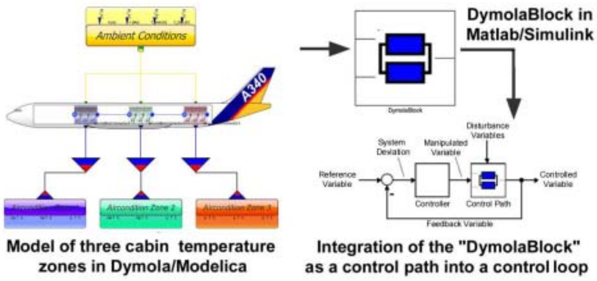

Fig. 8 *Schema of the export to Simulink™ and the integration of the Dymola Block into a control loop*

In Simulink™ the cabin model can provide a basis for controller optimization tools, e.g. MOPS [9], or can be integrated into control loops. As an example figure 9 shows a simulation result, where a generic cabin model is used as a control path for two different controller designs.

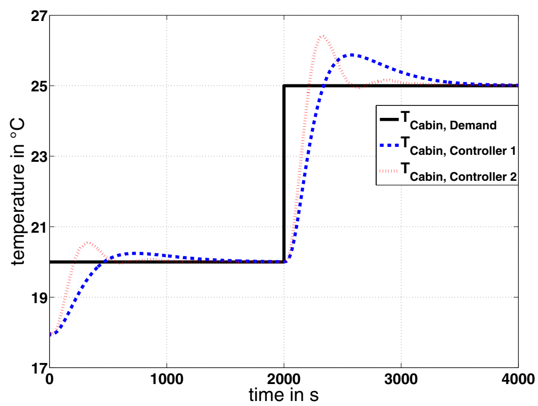

Fig. 9 *Response of a generic temperature controlled cabin model*

7 1D/3D COUPLING OF SYTEM AND FIELD SIMULATION TOOLS

As mentioned above, the correct simulation of the ducting is an important part in the layout process regarding passenger comfort. The ducting consists of ducts and more complex devices, like the mixer unit. It is state of the art to model the whole ducting with one-dimensional codes to simulate the air distribution and quality at the outlets. The complex devices are therefore approximated by combinations of simple pressure loss and mixing equations. To enhance accuracy and to get a better insight in the behaviour of this devices, CFD models should replace the one dimensional equations. A manageable approach to combine the sufficient one dimensional modelling of the ducts with the more accurate three dimensional models of the complex parts is code coupling, in this case 1D/3D coupling.

According to [16] there is no current realization for a tight 1D/3D coupling, i.e. two different simulations codes have to be used for the two domains.

There are several approaches in literature to realize the coupling of different codes. If the models cannot be implemented on one code, the different codes can be connected directly or indirectly by a so called middleware as illustrated in figure 10, [10]. The indirect coupling has the main advantage that each simulation code only needs one interface to the middleware. Then a coupling with every other code which provides a connection to this middleware is possible. This allows an easy to handle coupling process and provides a high flexibility in modeling.

Figure 11 shows a generic coupling example. Here a velocity profile (plug flow) is generated in Dymola™ and transfered as a transient boundary to the y-junction model in STAR-CD™. The calculated average pressure at the inlet is returned to Dymola™.
This approach will be examined with regard to the influence of the averaging method ([11], [5], [6], [1]) on the conservation equation and to the question, how large the CFD model has to be to capture the aspects of interest without losing to

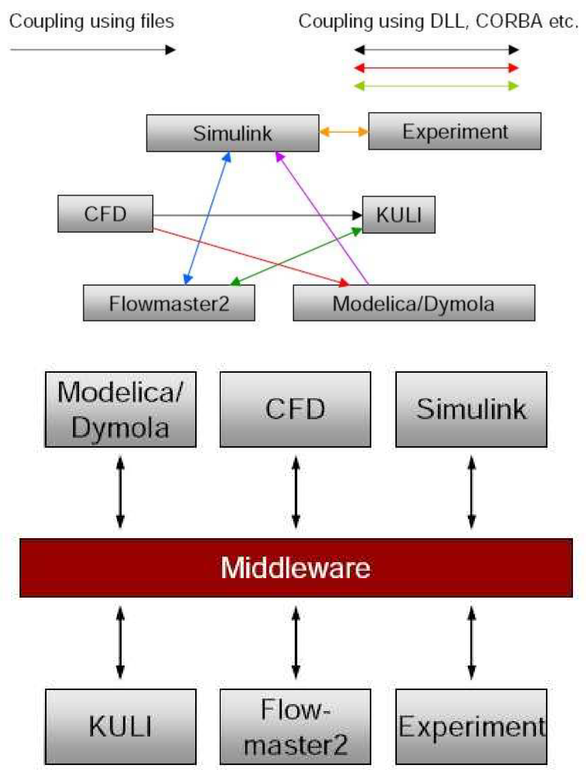

Fig. 10 *Code coupling approach without (left side) and with (right side) middleware [10]*

much CPU time. This task is outlined in figure 12.

8 OUTLOOK

Although first simulation results already look quite promising, the simulation models introduced in this paper do not describe the temperature behavior of a cabin in a satisfactory way. A reason for this is the limited availibility of proper flight test data, which is very expensive. Another approach to this problem could be the substitution flight test and test rig data with dynamic CFD simulation results. Besides replacing component models, e.g. the mixer-unit, by the coupling of 1D and 3D Code as described in chapter 7, another application of this approach could be the exchange of parts of the Modelica™ cabin model with 3D models in order to improve the accuracy of the simulation or to adapt parameters for the 1D model. By this technique it could be possible to setup a proper 1D simulation model

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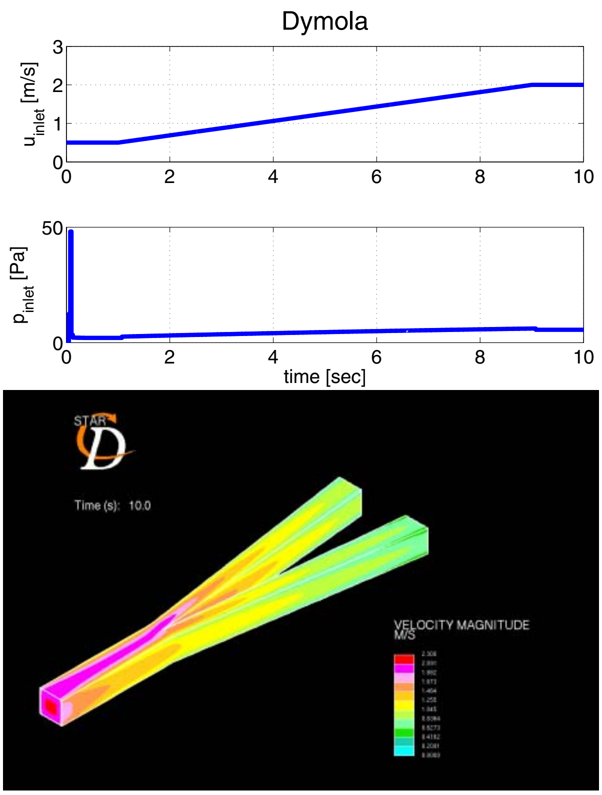

Fig. 11 *The inlet velocity is transfered from Dymola™ to STAR-CD™, which returns the average inlet pressure back*

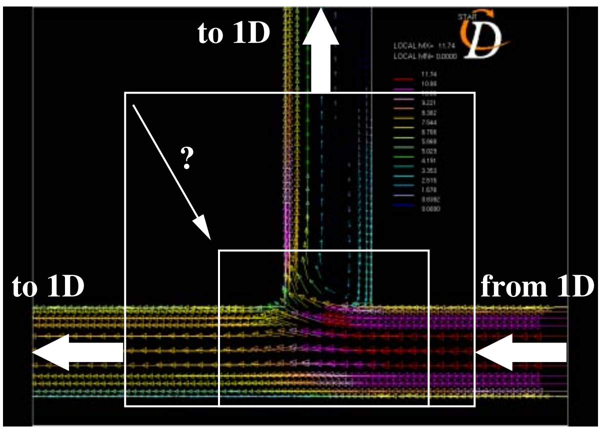

Fig. 12 *How small can the CFD model be to save computing time without losing the aspects of interest?*

for advanced controller design by simply translating existing CAD data and without the need of expensive measurements in the pre-production phase of an aircraft.

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