Modeling Sound Level and Pressure Loss in HVAC Duct Networks using a Framework in Modelica/Dymola

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Introduction

In the early phase of designing large HVAC duct networks the joint calculation of the sound level, air flow rate and pressure loss in the duct network as well as the prediction of the noise level in the passenger compartment gains more and more in importance. A unified framework for one-dimensional flow and acoustic simulation using Dymola/Modelica is introduced. As a tool for concept modeling it fulfills several requirements: The predictions methods used should be fast and computational efficient. It should use all kinds of data available, from analytic and (semi)empiric models to data obtained from measurements and acoustic and fluid dynamics computer simulations to characteristic diagrams and sparse point data given by component manufacturers.

The acoustic part is alternatively described by sound power based methods or plane wave two-port theory, the fluid mechanic part by pressure loss models. Each component either represents the acoustic or the flow part of a duct element or can, itself, be composed of both types allowing the modeling of non-standard components.

The object oriented approach provided by Modelica assures the extensibility of the models. It also allows the integration into a complete system simulation of the HVAC network. The simulation is easily set up using a GUI; an external parametrization ensures persistent data management and a smooth workflow. The resulting system of equations is automatically preprocessed and solved by Dymola.

Modeling Principles of Modelica

Modelica [1, 2] is an object-oriented language for acausal modeling of complex physical systems described by algebraic and ordinary time-dependent differential equations. Object-orientation means that systems are decomposed to objects, coupled by interfaces called connectors. Physical connectors contain pairs of physical quantities, a potential and a flow variable. This holds for many physical domains as given in Table 1.

In general, a pair of potential and flux quantities give a power; note that in some cases it can be advantageous to choose a different potential variable, like angle instead of angular velocity for rotational mechanics.

Domain	Variables	
	Potential	Flow
Electrical	Voltage	Current
Mechanics translational	Speed	Force
Mechanics rotational	Angular velocity	Torque
Thermodynamics	Specific Enthalpy	Heat flow rate
Fluid flow	Pressure	Mass flow rate
Acoustics	Sound pressure	Volume velocity

Table 1: Choice of state variables for connectors

For connections, i.e. at connected interfaces, the following rules hold:

1. Connected interfaces have the same potential.
2. The flows of connected interfaces sum up to zero.

The principle of acausal modeling is revealed by the fact that the modeler writes equations instead of algorithmic assignments, shown for an electrical resistor:

```
algorithm        // is v or i described
    v := R*i;    // by the ambient?
    i := v/R;

equation         // the tool takes care
   R*i = v;      // of the proper solution!
```

For differentiation with respect to time the derivative operator `der()` is used.

Modeling and validation of objects is independent of the later use, i.e. the boundary conditions at the connectors in an arbitrary system model. These principles enable the re-use of code, i.e. grouping the objects in libraries for use in different system models. These objects are used to synthesize sub-systems and in turn complex total systems in a hierarchical way.

Besides the integration of various domains in a complex system model, also cosimulation is possible via a standardized C-interface for external functions.

The language itself as well as the Modelica Standard Library is maintained by the Modelica Association [3]. The Modelica Standard Library is freely available and contains basic models from different domains, e.g.:

- Blocks: continuous control systems

- Electrical: single and multi-phase electrical circuits, models of electrical machines
- Mechanics: 1-D rotational and translational mechanics, 3-D mechanics of rigid bodies
- Thermal: 1D incompressible thermo-fluid flows and heat conduction models

Acoustic Modeling of HVAC Ducts

In modeling acoustics of duct networks, besides three-dimensional simulation techniques like FEM or BEM, two standard approaches are available:

First, the sound power-based description (SPD) has been widely used and forms the basis of the most standards and guidelines for the analysis of sound in ducts, e.g. see ASHRAE [4, 5] or VDI [6]. It can be applied for frequencies well above the plane wave cut-off. The sound power level of the connected ducts can be determined by summation of the transmission losses and generated sound power levels at every component from the fan towards the terminal sections of the network. All contributions resulting from wave reflections are neglected in this approach. This makes the prediction procedure very simple, but reduces the reliability considerably.

Second, the plane wave based description (PWD) of ducts, mufflers and networks [7, 9, 8] covers the low frequency range. A variety of analytical plane wave two-port models is available in the literature. The acoustical transmission matrix of non-standard components can be determined in 3-D FEM/BEM or unsteady CFD simulations in case of non-zero mean flow. In HVAC duct networks with their large lateral dimensions, however, the frequency range of plane waves propagation is rather limited. Nevertheless, accurate sound prediction at lower frequencies below a few hundred Hz is quite important, since absorbing liners are ineffective at those frequencies.

For the SPD components the sound power level (SPL) was chosen as the variable of state. A connector based on incoming and outgoing SPL represents the interfaces of the SPD one-, two- and multi-port elements. Left and right propagating SPLs do not interact within the elements. One-port sound sources, like the ambient, feed in a given SPL, two port sources, like a fan, add their noise contribution to the incoming SPL. In HVAC ducts the mean flow speed should be small, so convective effects are ignored in the SPD models. Flow noise caused by fans or regenerative elements like bends with vanes is included by adding terms depending on the Reynolds number, Strouhal number and drag coefficient.

The acoustic components based on the SPD approach are integrated into the Modelica library (see Fig. 1). It consists of active and passive one- and two-ports like silencers, filters, cross-sectional change, nozzle reflection, ambient termination or sources like fans of different type and flow-noise generating elements like bends with vanes. A simple indoor correction assuming point and line sources and a diffuse sound field can be used to estimate the sound pressure level of a single duct exit at given listener position. Plane wave models will also be added to the model library.

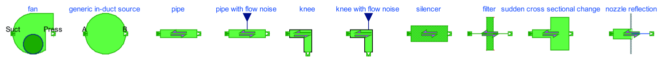


Figure 1: Examples of acoustic elements.

Flow Modeling

The 1-d modeling of air flow in HVAC ducts and other components is based on several approximations: The air flow in HVAC ducts with its with low Mach number is regarded as incompressible and steady state and fully stabilized. In most cases it is also turbulent. The state variables for fluid flow are the static pressure as the potential variable and the mass flow rate as the flow variable. The pressure loss coefficient $K = \frac{\Delta P}{\rho U^2/2}$ relates the pressure difference ΔP between the two ports of an flow duct element to the kinetic energy density of the flow. It depends on the Reynolds number, on the relative roughness and on the cross-sectional shape of the duct.

Analytic models, like the Colebrook-White equation, as well as measurement data, given as characteristic diagram or interpolated formula [10, 11, 12] or tabulated manufacturer data serves as input for the various flow models. Effects by turbulence, adverse velocity gradients, cross-sectional shape, surface roughness, curvature, interaction between elements in not fully developed flow regions result in corrective terms. Within the Modelica library flow elements for standard duct components are available (see Fig. 2).

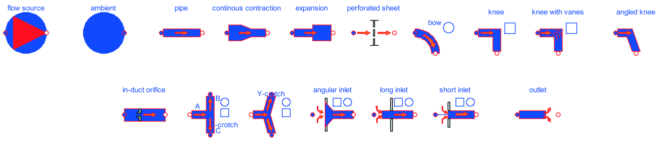


Figure 2: Examples of flow elements.

Modeling of Flow Noise

On the basis of acoustic and flow components, joint elements for components with flow-acoustic coupling can be easily assembled (Figs. 3, 4). The state of the fluid flow, the velocity and the pressure, is extracted and fed into the acoustic element where it triggers additional flow noise.

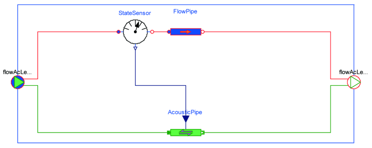


Figure 3: Example of a simple pipe with flow-acoustic interaction.

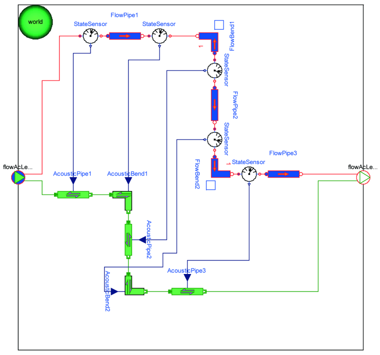


Figure 4: Example of a complex component with flow-acoustic interaction.

Workflow and Practical Issues

For the simulation of large HVAC duct networks a smooth work flow is essential. Networks are constructed by specifying components and connecting them. The Modelica tool Dymola [13] which is used here, provides a graphical user interface where networks are created by drag and drop. Dymola generates the program code automatically. Having set up a large network, one major task for a user-friendly operation remains, the parametrization. The problem, how to create parameter input files which can be filled from external data sources or manual input prior to simulation, and how to retrieve these data at simulation time, can be solved using a software-independent and self-describing data format such as XML. XML documents can be easily edited and may be integrated into any software capable for XML processing.

The first step is a detailed model analysis where the needed parameters are exported into an XML document for external input. This can be accomplished with simplified Modelica language parsers or internal functionality provided by some Modelica tools. The object structure of the model gives an XML document its tag representation.

After assigning values to the corresponding parameter tags, the second step is pulling these values back into the model at simulation time. This can be done using XPath, an inherent part of XML technology. An XPath expression forms the structural representation of an XML tag - here a parameter - thus will guide an XPath processor unto the tag retrieving the value at runtime. At start up of the simulation the XML document will be loaded into memory by an XML parser and all components will collect their parameter data via an XPath processor.

Dymola preprocesses and solves the resulting set of equations automatically. The simulation results will also be written into the XML document. So all data of the model, its structure, its simulation parameters and its results is encapsulated in one file ensuring a persistent data management. This XML document now holding all data is also used for postprocessing which is done externally since the postprocessing capabilities of Dymola are rather limited.

Examples

As a first example, the acoustical representation of a ventilation unit is given in Fig. 5. The predicted A-weighted SPL at each element is shown in Fig. 6. Prediction and measurement of the A-weighted SPL (Table 2) agree quite well.

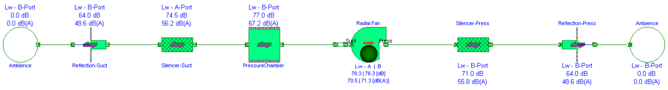
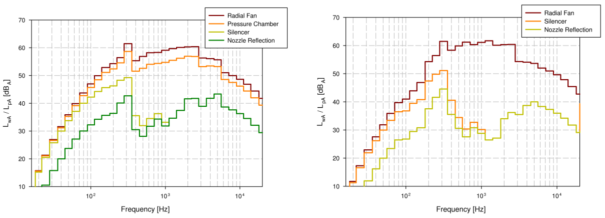


Figure 5: Acoustic representation of of a ventilation unit.



(a) (b)

Figure 6: A-weighted SPL in third octave bands at the suction side (a) and pressure side (b) components of a ventilation unit.

Position	Sound power level L_{wA}	
	Measurement	Prediction
Pressure Side	52 dB(A)	50.4 dB(A)
Suction Side	54 dB(A)	51.9 dB(A)

Table 2: Measured and predicted A-weighted sound power level of a ventilation unit

The same ventilation unit is the installed in a small duct network (Fig. 7). The predicted third band SPL at each element is shown in Fig. 8.

Conclusion and Perspectives

The Modelica library presented here includes standard models for describing 1-d acoustics and flow in HVAC ducts. Due to the object orientation of Modelica it can easily be extended, e.g., by condensation of humid air. It also can be easily integrated into a complete system simulation including the cooling circuit or the electronic control system, for instance. The 1-d simulations also could give the boundary conditions at the ventilation in- and outlet nozzles for a 3-d simulation of the flow and heat transfer inside a passenger compartment. For the prediction of the noise level inside a passenger compartment only a very simple one source to one receiver model available. Especially in the context of concept modeling where only coarse geometry data and estimations of the parameters are available, alternative 3-d methods are needed.

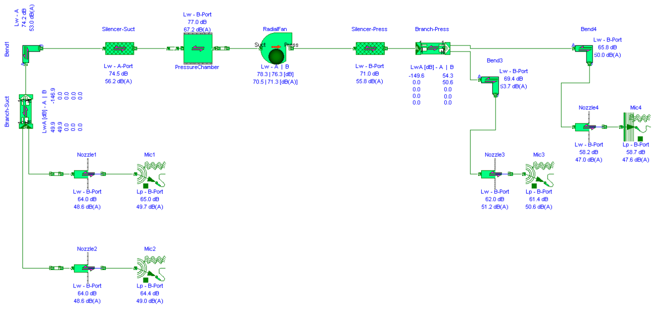
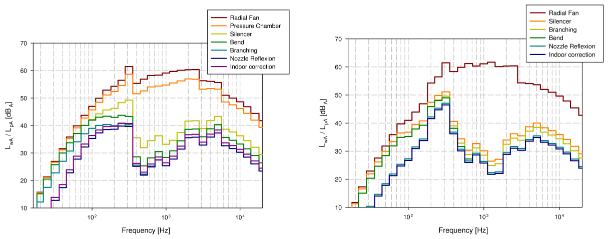


Figure 7: Acoustic representation of a ventilation duct network.



(a) (b)

Figure 8: A-weighted SPL at each element of a ventilation duct network along two paths from the fan to a listener, (a) at the suction side and (b) the pressure side

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