SIMULATION OF HELMHOLTZ RESONANCE EFFECTS IN AIRCRAFT ECS

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Abstract

Helmholtz resonators are closed volumes that are connected to pipes. They exhibit a pronounced resonance frequency, where small boundary pressure excitations in the volume or the environment lead to large mass flow excitations in the pipe. Aircraft have a topology similar to Helmholtz resonators, the closed volume is represented by the cabin, while the pipe is represented by the Environmental Control System. Some discrepancies appear due to the non-zero mass-flow or friction effects in aircraft ECS. Preliminary analyses showed, that resonance effects might still appear in spite of this differences. A detailed aircraft-level model of an ECS is presented in the equation-based modelling language Modelica. In simulations of this model, the appearance of Helmholtz resonance effects in aircrafts could not be confirmed.

1 INTRODUCTION

In environmental control systems (ECS) of passenger aircraft, limit cycles are always a potential concern. Limit cycles are bounded oscillations caused by nonlinear systems dynamics. Current modeling and simulation approaches are not perfectly up to the task of predicting related problems. This can result in additional flight tests later down the line, with corresponding costs.

A common approach is to split the air generation pipeline into bleed system, air conditioning pack, mixing unit/ducting system, and cabin. The control systems of those parts are then developed and simulated independently. Sometimes this approach is justified by the argument of a frequency split – the dynamics time constants of neighboring systems are supposed to be sufficiently different to not interfere. It is often suggested that the dynamics downstream only have a minor influence on the dynamics upstream. In any case, end results vary.

In literature, many modelling approaches for aircraft ECS are described. Most of them concern themselves with thermodynamic optimization of the process, see for example [7][6][3]; Here, transient effects are not relevant, therefore control system stability cannot be predicted with those models. In [2], air conditioning packs for ECS were modelled on different detail levels, corresponding to different design stages of the aircraft. In [4] and [5], electropneumatic bleed-air valves were modelled in the equation-based modelling language Modelica; These valves exhibit strong stick-slip behavior, and are assumed to be a fundamental cause for limit cycle oscillations in ECS.

While some of those works can help predicting control system instabilities, they consistently do not model the complete path of the bleed air from engine bleed to cabin. For reasons explained in Section 2, consideration of the complete system is crucial for accurate results.

In this paper we make the case that the entirety of aircraft ECS and cabin can be considered as a Helmholtz resonator, resulting in a pronounced resonance frequency on aircraft-level. We show how the topology of traditional ECS compares to Helmholtz resonators. Aircraft level transient simulation is presented as a necessary measure for reliable prediction of limit cycles. A suitable model and associated simulation results are presented to substantiate this claim.

2 HELMHOLTZ RESONANCE IN AIRCRAFT ECS

Helmholtz resonators were first described by Herrmann von Helmholtz in 1863 [8]. They are air-filled cavities connected to a pipe. When exposed to pressure variation, Helmholtz resonators exhibit a second-order behavior with low damping, i.e. a pronounced resonance frequency. This effect is used heavily in mid-tier audio equipment, where bass-reflex systems are used to increase efficiency.

The operating principle is similar to mechanical spring-damper systems or electric oscillating-circuits: Two modes of energy storage are connected and perfectly out of phase. An overpressure inside the volume drives the air out of the pipe, the inertia of this massflow causes the pressure-compensation to overshoot, resulting in an underpressure, and so on. This is illustrated in Figure 1.

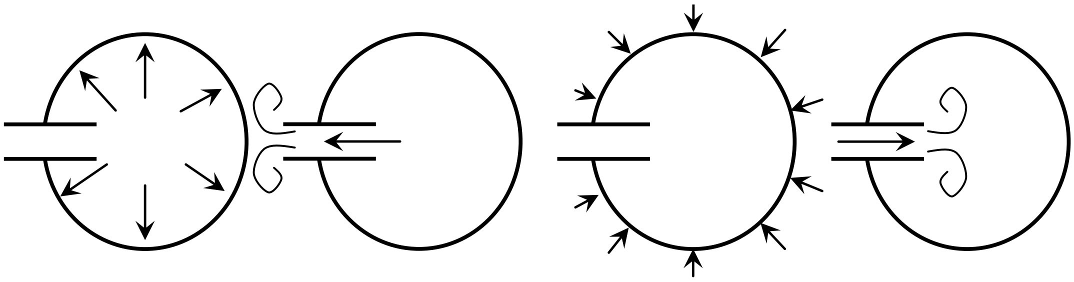

Figure 1 – Illustration of a Helmholtz resonator cycle

Aircraft ECS share their topology with aircraft resonators: The closed volume is represented by the cabin, while the pipe is represented by the bleed air system and air conditioning pack, which are connected in series. While the aircraft cabin is large compared to other examples of Helmholtz resonators like loudspeakers, the principle of operation is not limited by size. The only difference is the resulting resonant frequency, which is dependent on air volume, pipe length and pipe diameter.

Simulation of this phenomenon is straightforward. In Figure 2, a simple Modelica model and corresponding simulation results are presented. A cabin of $100\,\mathrm{m}^3$ is connected to a component representing two parallel pipes with a length of $10\,\mathrm{m}$ and a diameter of $0.15\,\mathrm{m}$. The pipes are subjected to a pressure chirp with an amplitude of $1000\,\mathrm{Pa}$. It can be seen that the resulting pipe flow exhibits a strong resonance at around $0.33\,\mathrm{Hz}$. The maximum amplitude of the pipe flow is $1.77\,\mathrm{kg/s}$.

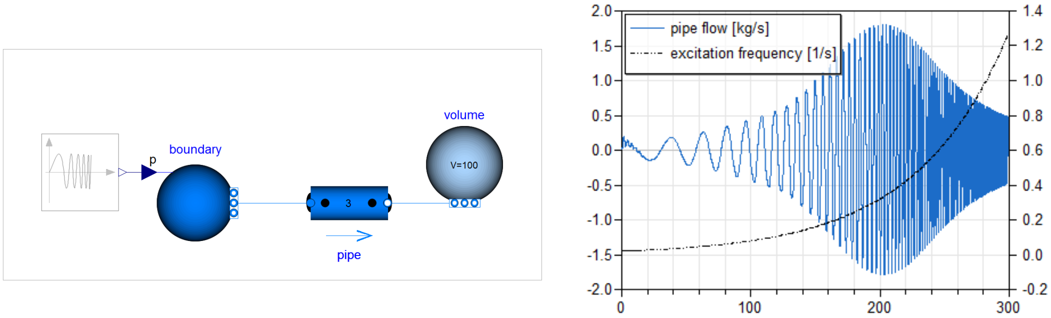

Figure 2 – Simulation of a Helmholtz resonator subjected to a chirp signal

Of course, ECS have some peculiarities: contrary to typical Helmholtz resonators, the pipe flow in ECS does not average to zero, and contain flow restrictions. To take this into account, the simulation was repeated with an added offset pipe flow of $1\,\mathrm{kg/s}$ and heavily increased friction. The result can be seen in Figure 3. The maximum amplitude of the pipe flow decreases to $0.55\,\mathrm{kg/s}$ and the resonant frequency stays at $0.33\,\mathrm{Hz}$. Still, the overall resonance effect is significant.

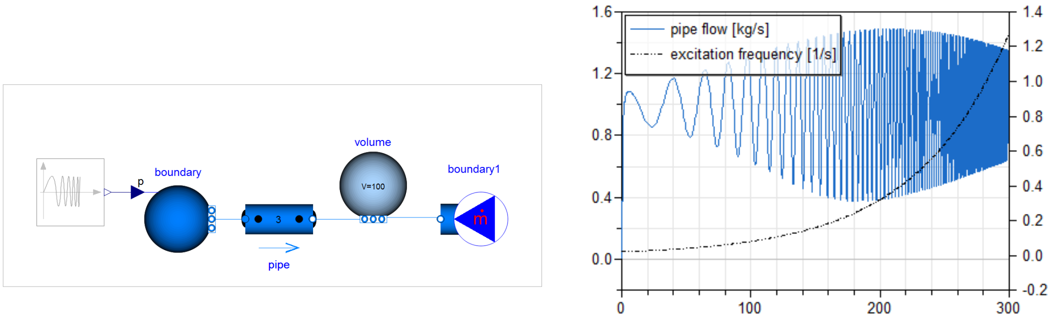

Figure 3 – Simulation of a Helmholtz resonator with extraction subjected to a chirp signal

This analysis is evidence that helmholtz resonance plays an important role in the system dynamics of aircraft ECS. To the best knowledge of the authors, this effect has not been considered on earlier aircraft projects. We found a single patent where Helmholtz resonance was given consideration for bleed air scoop inlet design [1], but no similar analysis was done on aircraft level.

3 SIMULATION OF AIRCRAFT ENERGY SYSTEMS

Of course, for final control system design, a much more detailed analysis is necessary. Aside from pipe friction, several other effects have to be considered: The air conditioning pack contains turbomachinery, which has its own inertia. Some air from the cabin is recirculated, filtered and ducted to the mixing chamber, where it is mixed with fresh air from the air conditioning pack. Several valves in the bleed air system actively control pressure and mass flow, interfering with each other as well with as the Helmholtz resonance effect. To adequately simulate an aircraft ECS, detailed modelling of the complete system is therefore necessary. An example for this is presented in the following.

Modelica was used as a modelling platform. The overall model contains 9 top-level components for the bleed system, 12 for the air conditioning pack, and 9 for ducting and cabin. It can be seen in Figure 4. For a more detailed look, let us separate the thermal, pneumatic, control logic and mechanical domains. All modelled effects are described in this Section.

3.1 Thermal Domain

Air bled from the engine compressor stages is far too hot to be directly ducted into the cabin. It can reach several hundred degrees Celcius. It is therefore precooled inside the engine fan (not included in this model), then ducted to the air conditioning pack. There it is cooled in the primary heat exchanger against cold ram air from the environment, and compressed again. The compression increases the temperature, increasing the efficiency of the main heat exchanger, where it is again cooled against ram air. Downstream, a combination of two heat exchangers, a water extractor and a turbine cool the air and decrease humidity. From there the air is ducted into the mixing

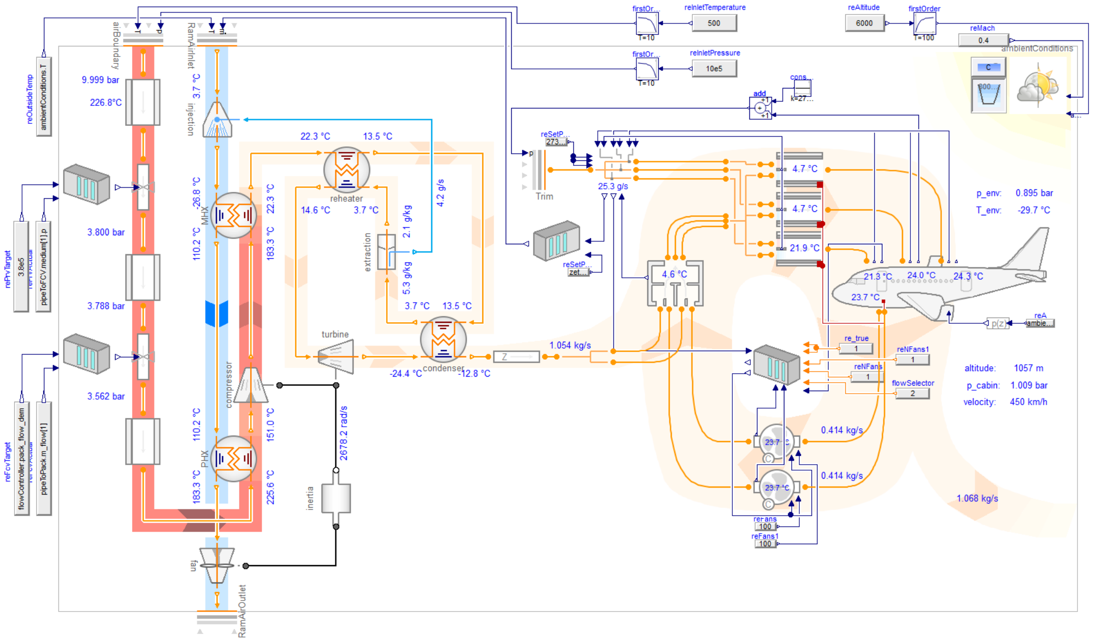

Figure 4 – Modelica diagram of aircraft energy system model

chamber.

The air enters the cabin through inlets at the top of the cabin, generating two longitudinal vortexes. These help with the mixing of the cabin air. Air then leaves the cabin to the underfloor volume throuth outlets near the bottom of the cabin. A portion of the cabin air is vented outside, the remainder is filtered and recirculated by fans into the mixing chamber. In the mixing chamber, the recirculation air is mixed with fresh air from the air conditioning pack and ducted into the different cabin temperature zones. The air in the mixing chamber has the correct temperature for one of the temperature zones, but is too cold for the others. For these zones, a small amount of uncooled bleed air is added to increase the temperature inside the ducting system.

Contrary to intuition, aircraft cabins have to be cooled rather than heated most of the time. Although outside temperatures can reach -70° Celcius, the cabin wall is well isolated, while the heat generation of passengers, cabin lights and inflight entertainment systems can be quite substantial. To keep the cabin at the desired temperature, the cabin energy balance has to be brought to zero by controlling the inlet air temperature.

3.2 Pneumatic Domain

Hot dense air is expanded through the Pressure Reduction Valve and the Flow Control Valve in the Bleed Air System. The distance between those valves can be quite substantial, resulting in a significant air mass in the connecting pipe. By extension, the corresponding inertia should be significant as well. This is relevant especially in this work, where we want to analyse if resonance behavior does in fact occur in aircraft energy systems.

Inside the air conditioning pack, air pressure is still much higher than ambient pressure. This energy is used to drive a turbine, which in turn powers a compressor. Excess power is used to power a fan that ensures airflow through the ram air channel when ram pressure is inadequate, for example during ground operations.

To distribute air evenly over the length of the aircraft cabin, a system of distribution- and riserducts is employed. In our work, the ducting system for each zone was modelled as a single pipe including a thermal inertia of the piping material. In a preliminary study, the discretization of this pipes was fitted in such a way, that the dynamic response closely matched the average response of the complete ducting pipe network.

While the air volume flow into the cabin is constant, a varying volume flow is vented into the environment through the Outflow Valve. During altitude changes, the target pressure of the cabin is adjusted to limit hoop stress on the fuselage. The Outflow Valve acts as an actuator to achieve this.

3.3 Control Logic

The Flow Control Valve regulates the mass flow of fresh air entering the air conditioning pack. Usually the target mass flow is set in such a way, that the air volume flow entering the cabin is constant.

The Pressure Reduction Valve regulates pressure downstream to a fixed value, to keep the connecting pipe within its design limits. Small devations are not necessarily problematic, but can degrade performance of the Flow Control Valve.

Temperature regulation inside the cabin is done by a cascading control scheme. For each temperature zone as well as the flight deck, a controller regulates the corresponding ducting temperature, to keep the cabin volume temperature at the target value which is provided by the pilot. The lowest of these ducting temperatures is in turn regulated by changing the pack temperature demand. All other ducting temperatures are then increased to their setpoint by adding hot trim air.

Pack outlet temperature is regulated by opening and closing the inlet of the ram air channel. Opening the channel results in a higher cooling mass flow (the blue mass flow in Figure 4), decreasing the outlet temperature on the warm side of the heat exchangers. In this work, the ram air channel is not modelled in detail, instead, ram air massflow is directly given by the controller outout.

Cabin pressure is regulated by the Outflow Valve, controlling the air mass flow from the underfloor volume to the environment. Target pressure is generated as a function based on altitude.

The speed of the recirculation fans is regulated to keep the recirculation air volume flow rate constant.

3.4 Mechanical Domain

The model features rotational inertias for the recirculation fans. Compressor, turbine and ram air channel fan include a common rotational inertia, as those components reside on a common shaft.

4 RESULTS AND DISCUSSION

Similar to the preliminary analysis as presented in Section 2, the complete system model was subjected to a bleed pressure chirp, i.e. a harmonic pressure boundary condition of increasing frequency (0.001 to 2 Hz) but constant amplitude of 0.1 bar. For the analysis, controllers for both valves in the bleed system were replaced by constant-blocks.

To estimate the significance of a Helmholtz resonance effect in aircraft ECS, the simulation was repeated, this time the dynamic impulse balance in all simulated pipes was turned off. That means that air was assumed to have no inertia. Without inertia, Helmholtz resonance is not possible, so the difference between both simulations gives some indication about the relative significance of the resonance effect. The resulting mass flows can be seen in Figure 5.

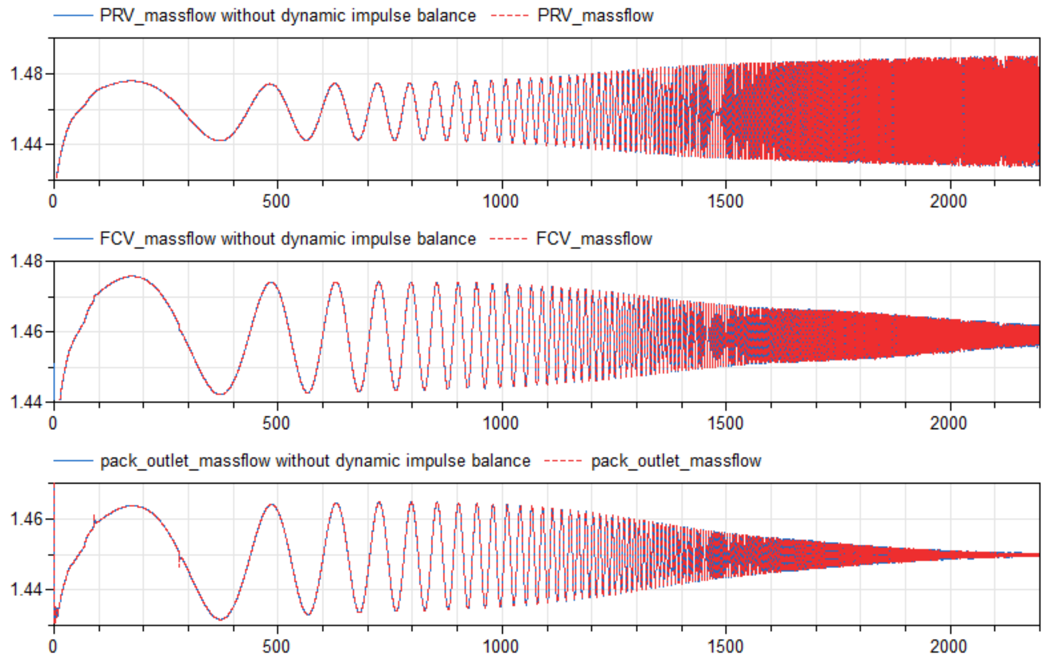

Figure 5 – Model response to bleed air pressure chirp (x: time [s], y: pressure [bar]

It is apparent, that there is no significant difference between both simulations. Contrary to the hypothesis of the authors, Helmholtz resonance doesn’t seem to play a role in the context of aircraft ECS.

Several reasons for this discrepancy are conceivable: First, the structure of an ECS does not exactly mirror classical Helmholtz resonators. The cabin is pneumatically divided from the underfloor volume, while recirculation air creates a pneumatic loop. Second, the behavior of the turbomachinery in the air conditioning pack can introduce additional damping. This is especially true for large mass flows. However, the simulations were repeated for strongly reduced mass flows, with no change in behavior. Third, the ratio between system inlet pressure and cabin pressure was much larger than in the preliminary analyses, resulting in a greater ratio of dissipated energy. Fourth, there is a strong coupling between the system and its controllers. The controllers of the bleed system, which were assumed to interact most strongly to the pressure oscillations were turned off in this analysis, but the remaining controllers may still play a role in the results.

While Helmholtz resonance doesn't seem to be of relevance in the context of aircraft ECS, other interaction effects between different subsystems might still occur. Aircraft-level physical simulation is the most reliable way of predicting this interactions during early design stages.

5 CONCLUSION

Helmholtz resonance is a physical phenomenon occuring in Helmholtz resonators - closed volumes connected to pipes. Aircraft ECS have a similar topology to Helmholtz resonators. However, simulations using detailed aircraft-level models show that no Helmholtz resonance effects occur in aircraft ECS.

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