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Masterarbeit

Determination of Heat Transfer Functions for a Rijke tube using 3D CFD and their application in 1D CFD

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8 Conclusion and Outlook

The present master thesis is about the development of models to describe thermoacoustic instabilities in a Rijke tube. The goal was to replace the heated wire geometry with a simplified model to reduce the numerical complexity. The determination was done with 3D CFD using ANSYS CFX. To reduce simulation time significantly the model was partly implemented in 1D CFD with Flownex. Self-exciting resonance oscillations caused by heated wires were investigated. A simple linear time-delayed model was assumed in the beginning, neglecting few thermoacoustic characteristics like frequency dependency. Afterwards a more precise model was established, since insufficient results were produced. Transfer functions to describe the linear part of the phenomenon were determined. Using the Wiener model approach, the identified transfer function was extended with a polynomial function to describe the nonlinear saturation process of the limit cycle.

As a first simulation a Rijke tube configuration with heated wires was set up in ANSYS CFX. It demonstrated the Rjike tube specific effects. The hot wires induced natural convection in a vertical tube. After a short amount of time when a mean flow settled the system began to vibrate at its resonance frequency and higher harmonics. The oscillation saturated and formed a limit cycle. The behavior at three different wire temperatures was observed.

In a first step the thermoacoustic effects of the wires were approximated by a function using constant coefficients for relations between the mean values of the heat release rate $\bar{\dot{Q}}$ and the velocity $\bar{v}$ and the their fluctuations $\dot{Q}'$ and v'. Frequency dependencies were neglected. A constant phase delay between $\dot{Q}'$ and v' was used. Every temperature case had its own specific parameters. These assumptions are a strong simplification of the occurring phenomenon. This was done to investigate if a rather minimalistic model is enough to represent the phenomenon approximately for specific Rjike tube configurations. One model only works for one specific temperature case.

Three models for three different wire temperatures were developed. They were implemented in ANSYS CFX and Flownex to investigate their functionality. The wire geometry was replaced by an empty space with a heat input, which calculates the heat release rate via the identified models. The models only produced reasonable results when the simulation had very specific setup parameters. Varying boundary conditions slightly didn't lead to self-exciting oscillations in ANSYS CFX. In Flownex the simulations often tend to explode when deviating from a (very specific) working solution. Since the model neglects important thermoacoustic characteristics and therefore will only work in very specific numerical setups, this approach was replaced.

To find a more general model an approach from King (1914) was used to describe the behavior of $\bar{\dot{Q}}$. A square root function determines the development of the mean heat release rate at varying mean velocities. Several steady-state simulations were carried out to identify it. Every temperature case has its own function. To improve this model in the future and make it more general the used coefficients have to be normalized by the temperature difference between the wires and the far flow field. This way one can determine one function for a range of temperatures.

An approach from control theory to describe dynamic systems was used to represent the linear part of the thermoacoustic instability. The relation between $\dot{Q}'$ and v' was investigated. Transfer functions were simulated to cover frequency dependencies of the oscillation amplitudes and phase delays predicted by Lighthill (1953). Vector fitting was used to fit them on frequency dependent simulations of the heated wires. They were transformed into state space models subsequently in order to obtain a representation in the time domain.

Using frequency dependent simulations with ANSYS CFX an agreement with Lighthill's theory for amplitude reduction and phase could be found. Different wire temperatures were observed. Since they followed the same trend only one transfer function for all was needed to be determined. Rijke tube simulations with the derived state space model (instead of the wires) show decent results compared to the simulations done to determine the model. A deviation of its frequency response can be found at high frequencies. Since the heat source acts as a low pass filter the effects on the oscillation at high frequencies are greater compared to low ones. To determine the model only a few simulations were carried out at higher frequencies. An improvement of its behavior can be achieved by using more results at high frequencies to fit the transfer function. However, the used state space model describes the linear time invariant behavior of the occurring oscillation nearly exact.

In a next step the approach of a Wiener model was used to expand the state space model in order to represent the saturation process. A nonlinear polynomial function was determined to describe the behavior at increasing amplitudes. At a fixed resonance frequency several amplitude dependent simulations were carried out. Again, the same trend could be found at different wire temperatures. One quadratic function fitted all results. Due to small differences in the emerging frequencies between the simulation with and without wires, the determined nonlinear function showed a small deviation compared to the simulated amplitude dependent results. Less attenuation at increasing amplitudes was observed.

In a final simulation the function for the mean heat release rate, the state space model and the nonlinear function were combined. A self-exciting oscillating could be established and comparable results (compared to the simulation with wires) achieved. The linear behavior was modeled nearly exact while the nonlinear part still differed slightly. As a consequence of the model the systems 3rd harmonic got excited. It raised the general amplitude above the value to be achieved in the nonlinear part.

A reduction in simulation time could be achieved. The removal of the wire geometry in the tube decreased the needed mesh elements. Less computational power was needed. The simulation of the Rijke tube with wires took around 3 days. Without wires, but with the determined model for them, it only needed 2 days to simulate. An implementation of the final model in Flownex couldn't be achieved properly in the time of the present thesis. In a future work this implementation can be done to reduce the simulation time from days in 3D CFD to hours in 1D.

Improving the determination of the state space model with more results and refining the nonlinear function will lead to even better fits. This will be needed to improve final accordance of the model with the original heated wires in the Rijke tube. However, the model developed in the present thesis can predict characteristics of the occurring thermoacoustic instabilities. The linear growth of the oscillation amplitude is represented nearly exact, but the nonlinear saturation process needs to be improved to reduce an overestimation of the limit cycles amplitude.