Master thesis project:

Design, control and testing of a travelling wave thermoacoustic machine for energy harvesting

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Thermoacoustics studies phenomena where the interaction between acoustic wave and heat transfer effects plays a crucial role [1]. These include special types of heat engines and refrigerators where the conversion heat-work is performed by exploiting pressure waves, and not employing moving parts as done in standard engines. Thermoacoustic machines have a high potential for the development of sustainable and reliable energy systems, and this has stimulated a large body of research on the topic [2]. At the Automatic Control Lab (IfA), several student projects were carried out in the last few years to advance knowledge in this field. Some of them had a great experimental focus and lead to the successful construction of laboratory-scale machines, e.g. thermoacoustic refrigerators [3], Rijke tube [4].

1 Description

The project aims to investigate and demonstrate the potential of thermoacoustics for energy harvesting. As known from the literature [5], this goal can be pursued in conceptually different ways. For this project, a multi-stage traveling wave thermoacoustic machine has been identified as promising test bed. The main reason for this is that, while standing wave devices are more common, travelling wave ones generally feature higher efficiencies due to the fact that the gas undergoes a Stirling-like cycle with improved heat transfer [6]. Experience on this particular setup has been gained at IfA thanks to a previous master project [7] and a collaboration with one of the leading companies in the sector, namely *Aster Thermoacoustics*. The latter provided a demonstrator which is pictorially depicted in Fig. 1, and represents a laboratory scale version of the novel concept presented in [8].

The setup features two thermoacoustic engines, where takes place the conversion process through which the heat transferred between two heat exchangers triggers acoustic waves (of a travelling nature). An advantageous feature of the system is its modularity, which allows the thermoacoustic engine stages to be used individually and thus alternative architectures to be tested.

The project combines theoretical, numerical, and experimental tasks, and can be broadly divided in 4 steps.

Step-1. The first instrumental step consists of gaining a sufficient knowledge of the physical mechanisms underlying the available experimental setup via first-principles modeling, which can be aided by open-source software (e.g. *DeltaEC* from Los Alamos National Laboratory, *SPICE* from University of Berkeley). An interesting outcome of this step will be the comparison between the performance of standing wave and travelling wave machines. Since it is well known that the latter present various advantages, their analytic characterization, especially from an energy harvesting perspective, is highly desirable.

Step-2. The next step consists of assembling and operating the setup in Fig. 1, which has been successfully tested upon delivery but not used in a research project to date.

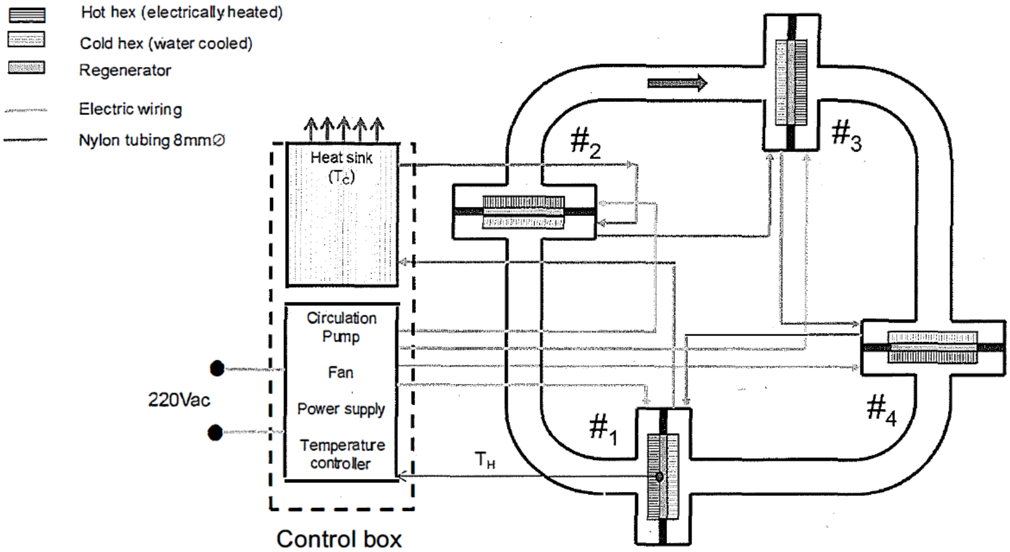

Figure 1: Pictorial representation of the demonstrator (note that the actual demonstrator only features two engines).

Step-3. In this step, harvesting solutions will be investigated and then designed. Among the existing methods for the acoustic to electric conversion [5], piezoelectric transducers seem the most viable solution for this project in terms of cost and ease of deployment. However, known issues of piezoelectric harvesters include low efficiency and achievable output power. For this reason, it is envisaged the opportunity to develop advanced solutions, including the adoption of dynamic magnifiers [9, 10], which have been shown to represent a very promising strategy to increase the performance and also to decrease the critical temperature gradient for self sustained oscillations. Analytical predictions of the harvesting solutions will be performed, building on the models considered in Step-1, and the successful solution will be tested.

Step-4. The final part of the research aims to demonstrate the potential of feedback control to improve on the energy harvesting performance achieved in open-loop. Using the first-principles models developed in Step-1, and taking in consideration the experimental evidence from Step-2 and Step-3, active control strategies will be proposed to maximize the performance objective (e.g. total generated power), and address limitations arising in these thermoacoustic machines. For example, the variability of external heat source (e.g. waste heat) introduces potential difficulties in matching the impedances (acoustic and electric) of the systems. Moreover, there exists a minimum temperature difference between the exchangers (depending on the machine layout) which is needed to successfully extract energy.

It is finally noted that very little work has been done on traveling wave engines with piezoelectric harvesters, hence this project, by looking at the problem from various perspectives (experimental, numerical, feedback control) has the potential to contribute to the state of the art in the field.

2 Goals and tasks

Based on the discussed description of the problem, the project is articulated around two main phases.

2.1 Modeling and testing of a traveling wave thermoacoustic machine

The goals of this phase, which consists of Step-1 and Step-2, are:

- deriving a model of the system and validate it (or complement it) with open-source codes;
- assembling the *Aster Thermoacoustics* demonstrator and performing functional tests.

2.2 Design, implementation, and control of energy harvesting solutions

This phase coincides with Step-3 and Step-4 of the project description, and will focus on:

- designing an energy harvesting strategy for the available setup;
- testing the system and identifying possible changes that would improve the achieved performance;
- designing a control system which addresses the detected issues.

2.3 Work flow and possible timeline

The project's main tasks, together with a possible timeline, are briefly recapped in the following:

- literature review on thermoacoustic engines with focus on harvesting - 0.5/1 month ca.
- modeling of the multi-stage traveling wave thermoacoustic machine based on first principles - 0.5/1 month ca.
- experiments with the *Aster Thermoacoustics* demonstrator - 0.5 month ca.
- design and testing of a harvesting strategy - 1/1.5 month ca.
- investigation on feedback control solutions to improve the harvesting performance - 1 month ca.
- write-up dissertation - 1 month ca.

Beneficial skills (or interests) of the prospective applicant: modeling physical systems with first principles; experimental testing; control design.

References

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