FLUIDIC OSCILLATIONS AS ENERGY SOURCE FOR FLOW SENSORS

José I. Ramírez[1*], Friedemann Tonner [1], Axel Bindel[1]
[1]Department of Energy Efficient Mechatronic Systems, Fraunhofer Technologie-Entwicklungsgruppe, Stuttgart, Germany

Abstract: Fluidic oscillations can be used as an energy source for self-sufficient sensors. We designed, simulated and tested a fluidic oscillator based on the Coanda effect. It is able to work within media like air and water. Preliminary measurements show that our oscillator can harvest approximately $150\mu W$ of power by coupling a piezoelectric chamber to one of its channels. Future work will be focused on optimization of oscillators with the help of an automation tool in order to offer an integrated self-sufficient wireless sensor node.

Key words: Fluidic oscillator, energy harvesting, Coanda effect, edgetone generator, piezoelectric converter, flow sensor, resonance, self-sufficiency, wireless sensor node.

1. INTRODUCTION

We simulated designs and prototyped models of fluidic oscillators which were able to work in different fluids. In air they harvest approx. 150µW of electric power by coupling a piezoelectric chamber to one of its feedback arms. This first result opens the possibility of having an integrated design in which for example, a flow sensor is not only measuring flow rate but also collecting its required energy from the flow. The next efforts will be in the direction of developing optimization methods based on genetic algorithms in which the geometry parts will be varied until a maximum amount of scavenged energy is reached.

The outline of the paper is the following: Section 2 explains the characteristics and principles of operation of the fluidic oscillator designed. Sections 2.1 and 2.4 explain two different principles for generating fluidic oscillations, first the coanda effect fluidic oscillator and second the edge tone generator. The coanda effect fluidic oscillator works both in compressible (e.g. air) and incompressible media (e.g. water). On the other side the edge tone generator is a device intended to work in compressible media. Sections 2.1 and 2.3.talk about the results of the Coanda fluidic oscillator operated in air and in water Section 3 discusses the tools we are using to design and validate our oscillator models. Section 4 concludes and gives an outlook of the future steps in order to have a complete optimization tool that will help us propose tailored oscillator shapes for specific fluids, flow regimes, and required energy output.

2. FLUIDIC OSCILLATIONS: PRINCIPLES AND RESULTS

2.1 Principle of Coanda effect fluidic oscillators

The Coanda effect or wall attachment effect (see Figure 1), is the phenomenon that occurs when a fluid jet entrains the fluid near the walls of a chamber. The presence of walls causes molecules of the fluid to be evacuated between the jet and each wall. This leads to a low pressure region between the jet and walls, making the jet to attach to either side [1]. The jet can be attached or detached to either side when an adequate positive control pressure is applied. The control pressure doesn't have to be as strong as the main jet pressure. This enables the construction of bistable elements similar to flip-flops known from digital logic.

A periodic oscillation is obtained when the outputs are fed back to the control inputs on each side as in Figure 2. By coupling a chamber containing a piezoelectric bending membrane as a wall to the output, a change in pressure deforms the membrane. Via the piezoelectric effect, mechanical deformation is converted to charge separation, thus generating an electric voltage.

In this setup the oscillation is widely independent on the loading of the outputs. The principle works even with blocked outputs because vents are relieving the jet. Although when the output is blocked, the available pressure that the output feels can be up to 80% of the power jet pressure [1].

* Contact author: Tel. +49 711 970 3737, email: jsr@teg.fraunhofer.de

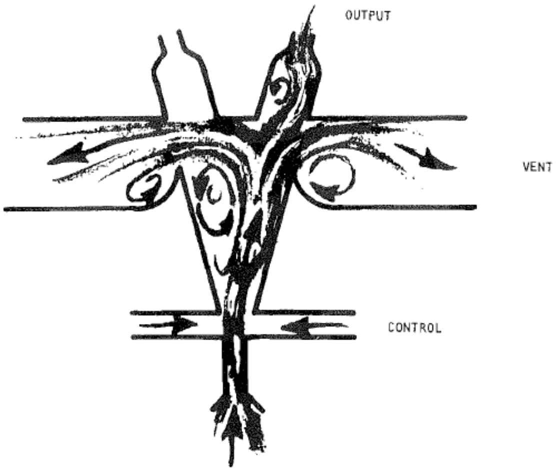

Figure 1: Coanda effect in a bistable switch: A jet enters the nozzle below and is deflected to either wall and exists in one of the two outputs or vents. A control signal from the side can deflect the jet (from [1]).

2.2 Results of a Coanda fluidic oscillator operated in air

We designed a fluidic oscillator based on the Coanda effect and simulated the design (see Figure 2). Some simulation steps showing the wall attachment effect can be seen in Figure 2: Lighter shade indicates a high jet velocity (the lightest shade in the middle of the jet is 7m/s). The top left image (labeled with “1”) is an earlier time frame than the following images (labeled with a 2, 3 and 4 in this chronological sequence). The jet from below attaches to the left and right walls by the Coanda effect alternatively.

In Figure 3 we depict the periodic changes in pressure resulting from the simulation of the design. At a flow rate of 5l/min an oscillation frequency of approximately 1kHz is attained. The simulation is calculated in two dimensions with closed boundary conditions. This corresponds to a model with infinitely extruded walls and has to be taken into account when comparing simulation results and measurements.

We used rapid prototyping to convert the design in to a working model. An exploded view of the different layers of an integrated design with piezoelectric disks is shown in Figure 5 a). The assembled model is depicted in Figure 5 b) together with the prototype model for measurements in air (without integrated piezoelectric). The dependency of the oscillation frequency and the power output on the flow rate can be seen from the measurement data in Figure 4.Such results where obtained by connecting a chamber with a piezoelectric disk in the feedback arms. The absolute frequency of oscillation from the simulation is mainly in agreement with the measured result of the prototyped model: 1.4kHz measured vs. 1kHz simulated at 5l/min. The linear dependency of the frequency on flow rate [2] is measure as expected.

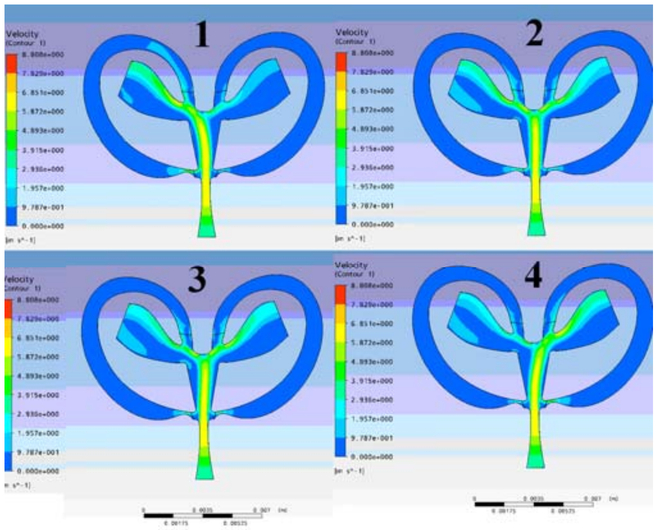

Figure 2: Simulation of Coanda fluidic oscillator design: Velocity profile coded by shading in the inside of geometry. The jet from below attaches to the left and right walls alternatively.

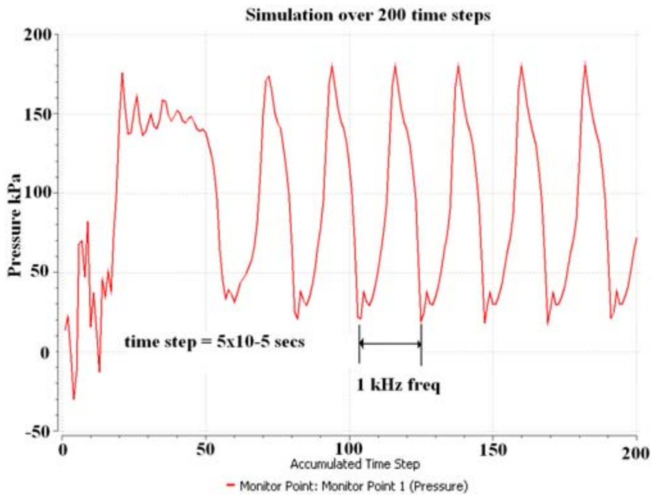

Figure 3: Simulation: Air pressure over time in one of the oscillator feedback arms at a flow rate of 5 l/min. See the agreement with model results in Figure 4.

We see in the power output (Figure 4) a peak resulting from the resonance frequency of the combined fluidic chamber and piezoelectric disk setup. At approx. 6l/min. we attain an electrical power output of 150µW. By tuning to resonance, the energy conversion from mechanical energy to electrical energy can be optimized by limiting oneself to a narrow frequency range.

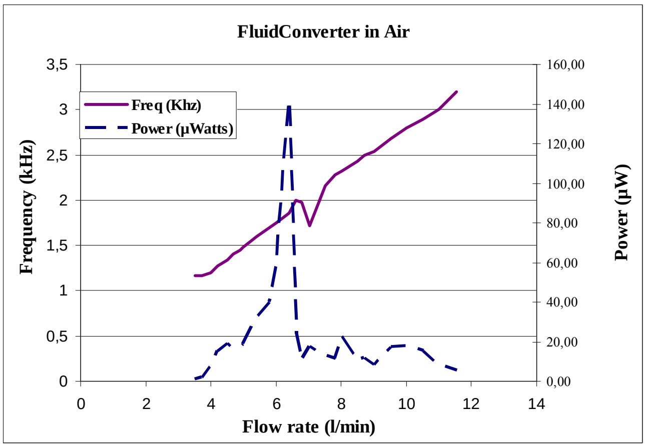

Figure 4: Oscillation frequency and electrical power output over flow rate in the prototyped oscillator mode in air. The preliminary measurement data shows a small notch in the frequency response that may be attributed to a measurement error.

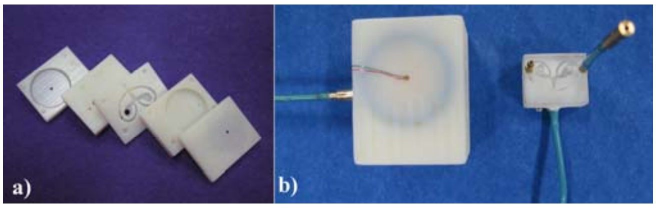

Figure 5: a)Exploded view of a fluidic oscillator design with integrated piezoelectric chambers (circular disks over and under the oscillator).b) Integrated design on the left in comparison to the first working prototype for air on the right.

2.3 Results of a Coanda fluidic oscillator operated in water

The geometry that we see on the left side in Figure 5 b) was first tested in air and later in water. Oscillations where detected in the system (Figure 6 a). These oscillations are two orders of magnitude slower than the oscillations obtained in air for the same volumetric flow rate. This scaling is expected because of the density and viscosity difference between water and air. Although detecting exactly how many times the oscillations in air are faster than the ones in water are out of the scope of this paper, we can say that this is strongly related to the difference in Reynolds numbers and the dynamic viscosity of the two fluids.

The quantitative agreement of the simulation results can be observed in Figure 6 b), where the simulated frequency of the system at the same flow rate gives a result of 43Hz, compared to a measured frequency of 45Hz.

The energy scavenged in water is about two orders of magnitude smaller than in the case of air (see Figure 7). This is due to the lower frequency of the oscillations and the high stiffness of the piezoelectric disks resulting in off-resonance operation. Piezoelectric membranes designed to bend near to its maximum allowed stress under the calculated pressure values will be part of further steps towards an integrated sensor.

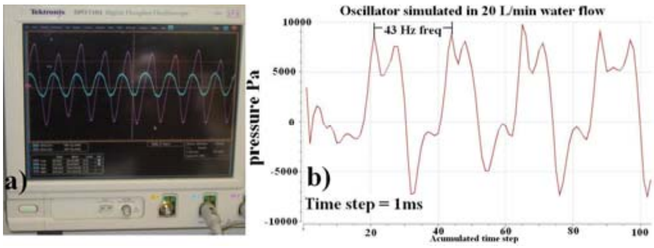

Figure 6 : a) Voltage output of the two piezoelectric chambers over time. The flow rate is 20l/min water. Frequency is 45Hz (time interval shown on screen is 200ms). b) Pressure over time in feedback channel of the Coanda fluidic oscillator when simulated in water at a flow rate of 20l/min. Pressure oscillates at 43Hz.

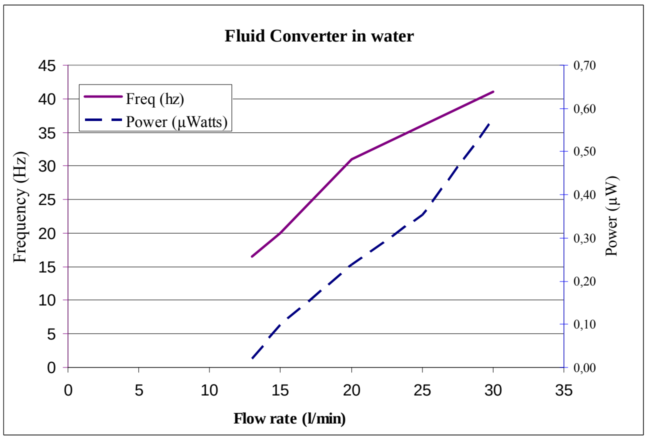

Figure 7: Frequency and power output over different flow rates for the prototype model in ***Fehler! Verweisquelle konnte nicht gefunden werden.****.*

2.4 Principle of edge tone generators

The edgetone generator is a geometry that works with compressible fluids (air, gas). The geometry behaves like a coupled spring-mass system, in which the compressibility of the fluid and the volume of the chamber play an important role to obtaining such oscillating behavior. The resonant chambers oscillate at a frequency that is proportional to the input flow rate and length of the chamber (half of the wave length). For further details on edgetone generators see [3].

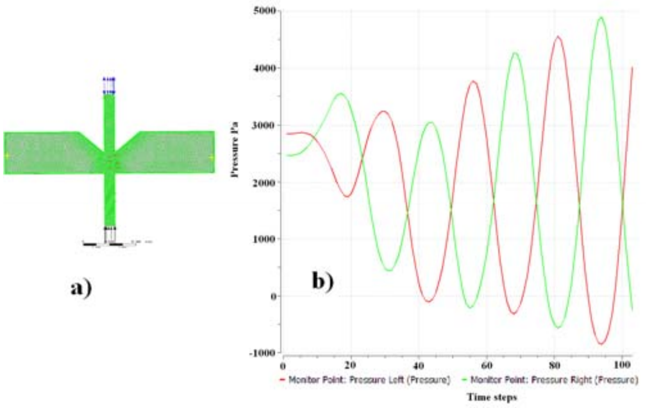

Figure 8: a) Meshed simulation model of the edgetone generator. b) Pressure in the edgetone generator chambers over time when there is a pressure difference of $\Delta p = 5kPa$ between input and output. The simulation shows an oscillation frequency of around $4kHz$*.*

The advantage of the edgetone generator is that the frequencies generated in air can be easily matched to the resonance frequency of the piezoelectric disks by the size and volume of the chambers. Also the dimensions of the piezoelectric disk and the chambers can be matched. In Figure 8 the design was optimized for a frequency of $4kHz$. This means that the results in the future experimental setups based on such geometries should give a higher electrical output power than from a Coanda fluidic oscillator in air.

3. DISCUSSION ON THE DESIGNS AND VALIDATION OF THE MODELS

In the search of the first working prototype we followed different strategies. At first it was decided to make only virtual prototypes for Computational Fluid Dynamics (CFD) but the uncertainty of the results made us start looking for alternatives of how to validate such models. This especially applies when starting with a totally new geometry, without much insight of what could be the parameters expected from the simulations.

Another important issue was to confirm the validity of the simulation tools and replicating known results. A reference example is the well studied edgetone generator analyzed by Zipser et. al. [3] by means of refractometry methods.

Our process then evolved in designing the prototype in Computer Aided Design (CAD), then we generate the CFD mesh and simulate the geometry and to see if there were promising results. Once the results were obtained from the simulation, the prototypes were sent to manufacture by rapid prototyping in order to validate the simulated results with measurements. Many of the ideas of the geometries have been adapted from the theory of fluidic logic devices that started to gain importance before the boom of the integrated circuit (50´s to 70´s) [1]. Some ideas have been applied in recent years not only for sensing water flow but also for lab-on-chip applications or mechanical vibrating tools [2].

For oscillating geometries that work with compressible fluids, there is the possibility of analyzing and validating the model with laser vibrometry [3,4].

4. CONCLUSION AND OUTLOOK

This agreement between the simulated geometries and the measured results of the prototypes, gives us the possibility of thinking of an optimization procedure in which the geometries proposed can be given different parameters (nozzle diameter, channel width, etc.) in order to maximize an optimization target (For example, maximum pressure change). These optimized models can then be adapted into a design that encloses the complete functionality of sensor/scavenger. Such elements will later be integrated as an additional piece of pipe that will have the capability of monitoring its flow and pressure without disturbing significantly the entire system. Such integrability into water/fluid systems together with the advantage of a maintenance free system will lead to low-cost monitoring solutions.

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