Coupling of bio-inspired, nonlinear acoustic sensors for sound pre-processing and bandwidth tuning

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Summary: Most sensory systems in biology exhibit properties that resemble the behaviour of nonlinear dynamic systems [1]. The auditory sensing system is no exception with its nonlinear transfer characteristics enabling amplification and selection features [2]. It was suggested that biological auditory sensing can be modelled as a system tuned near/at a Hopf bifurcation [2]. Theoretical studies showed that the tuning to the bifurcation point can be achieved also if sub-threshold Hopf oscillators are coupled via their output signals [3]. Here, we study experimentally and numerically the properties of a nonlinear cantilever-based acoustic sensing system in dependence of the coupling strength. We show that coupling not only yields a transition between linear and nonlinear characteristics and increases sensitivity but it can be used for bandwidth enhancement of the system as well, enabling coverage of larger frequency ranges.

Introduction

Introducing bio-inspired signal pre-processing into speech and sound processing system strongly increases the performance, as recently shown by Araujo et al [4]. The main pre-processing components are thereby frequency decomposition of the signal, nonlinear (compressive) amplification, and adaptation of sensing properties to different inputs. Nevertheless, software-based implementations prevent real-time performance and high efficiency. Thus, hardware-based implementations are required. These can further improve the signal-to-noise ratio and the above mentioned properties if implemented into the sensing stage directly. We developed an acoustic sensing system with integrated bio-inspired pre-processing based on a silicon cantilever beam with real-time feedback [5]. Thereby, frequency decomposition is obtained using resonant operation. We demonstrated that nonlinear operation similar to a Hopf oscillator can be obtained using certain real-time feedback mechanism [5]. Since the linear or nonlinear characteristics are controlled by the feedback loop, dynamic adaptation of sensor properties can be introduced easily.

The exact mechanism, generating nonlinear dynamics in the inner ear, is still under discussion [6]. However, one proposed mechanism is coupling of the receptor cells and/or the hair bundles on top of these cells. This coupling increases the tolerance against noise and improves the range of non-linear regime [6]. Gomez et al. [3] theoretically showed that coupling of sub-threshold Hopf oscillators can induce a bifurcation as well. This yields an increase of the parameter range for the occurrence of the Hopf bifurcation and improves the sensitivity of the complete system. Here, we study the influence of output-signal coupling on the properties of our acoustic sensing system, consisting of nonlinear cantilevers. In particular, we analyse (i) if a Hopf bifurcation can be achieved due to the coupling, (ii) how the critical coupling strength depends on the sensor properties, and (iii) how the coupling affects sensor properties like sensitivity and bandwidth.

Implementation

Figure 1 schematically shows the coupled cantilever system. We use micro-electro-mechanical systems (MEMS)-based silicon beams with integrated deflection sensing and actuation [7]. After a first amplification stage and decomposition of the sensing signal x into an AC and a DC part using a high-pass and low-pass filter, respectively, feedback and output-signal coupling are realised using the FPGA structure of a STEMLAB-125 board. Two cantilevers with different characteristic frequencies ω are coupled and analysed. Coupling is implemented by first multiplying the sensing signal x_1 of one cantilever by the coupling factor C_f, then adding an offset u_{DC}, and finally using the resulting signal $y_2 = C_{f,1}x_1 + u_{DC}$ to drive the actuation of the second cantilever (see figure 1). Similarly, the signal x_2 from the second cantilever drives the actuation y_1 of the first cantilever. The coupling between both cantilevers is symmetric, i.e. $C_{f,1} = C_{f,2}$. Furthermore, self-feedback given by a_1x_1 is added to the actuation signal, yielding $y_1 = C_{f,1}x_2 + a_1x_1 + u_{DC}$. In this work, the critical coupling strength $C_{critical}$, at which the bifurcation is observed, is determined in dependence of the characteristic frequencies $\omega_{1,2}$ of the sensors and the distance $\mu = a_{crit} - a_{1,2}$ of the feedback strength a from its critical value a_{crit} at the Hopf bifurcation. Then, the response of the sensing system to sound stimuli of various frequencies and amplitudes is analysed.

Results

Figure 2 shows the critical coupling strength $C_{critical}$ in dependence of the ratio of characteristic frequencies ω_1/ω_2 of the two coupled cantilevers and the distance μ from the Hopf bifurcation. It is observed that $C_{critical}$ increases, if ω_1/ω_2 or μ increase, as was expected from the theoretical studies of Gomez et al. [3]. However, for a fixed ω_1/ω_2 and increasing μ, the slope of $dC_{critical}/d\mu$ is decreasing in the experiment while it is increasing for the theoretical prediction by Gomez etal., which is based on a normal form for the Hopf oscillators. To study, if this deviation arises from the coupling mechanism or the oscillator model, we will compare the experimental results with simulations of the system, using a sensor-specific model, and simulations of an adapted Gomez system.

Regarding the sensing properties, we observe higher sensitivities for the coupled system, as expected from the theoretical predictions. Nonlinear transfer characteristics occur, if the system of both cantilevers is tuned near the bifurcation point. Additionally, the range of frequencies, for which the system is sensitive, increases strongly (up to 10 times larger bandwidth). In this case, both sensors do not only show a stronger response to sound frequencies at the two characteristic frequencies, but also in the frequency range in between. This enables bio-inspired acoustic sensing systems covering the auditory frequency range with only a few cantilevers with nonlinear characteristics.

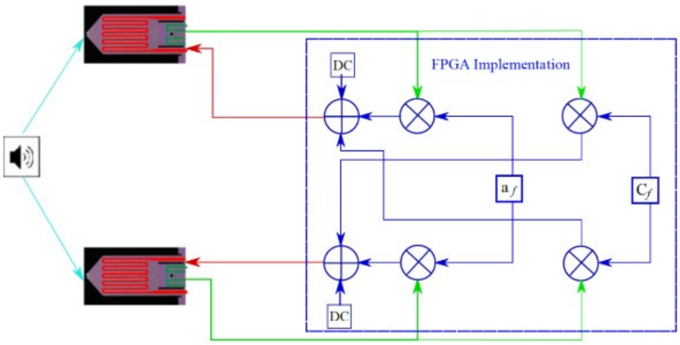

Figure 1: Schematic for feedback and coupling mechanism

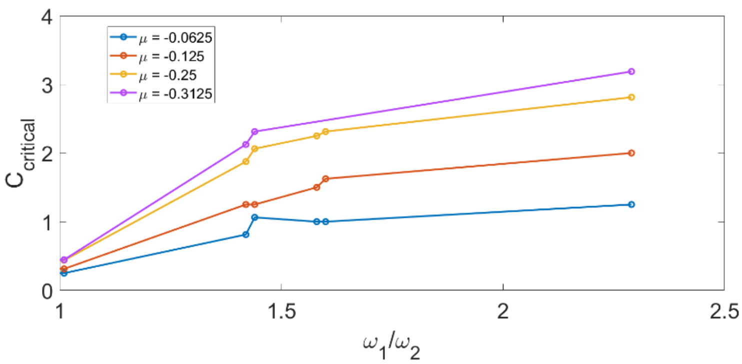

Figure 2: $C_{critical}$ as a function of ω_1/ω_2 and μ for different pairs of coupled cantilevers obtained from experiments.

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References

[1] Kandel E. R. (2013), *Principles of Neural Science*. McGraw-Hill Education Ltd.

[2] Hudspeth A.J., Jülicher F., Martin P. (2010). A critique of the critical cochlea: Hopf-a bifurcation is better than none. *J. Neurophysiol.* **104**(10): 1219-1229.

[3] Gomez F., Lorimer T., Stoop R. (2016) Signal-coupled subthreshold Hopf-type systems show a sharpened collective response. *Phys. Rev. Lett.* **116**(10): 108101.

[4] Araujo F.A., et al. (2020). Role of non-linear data processing on speech recognition task in the framework of reservoir computing. *Sci. Rep.* **10**(1):1-11.

[5] Lenk C., et al. (2020). Enabling Adaptive and Enhanced Acoustic Sensing Using Nonlinear Dynamics. *2020 IEEE International Symposium on Circuits and Systems (ISCAS)*.

[6] Ashmore J., et al. (2010). The remarkable cochlear amplifier. *Hearing research* **266**(1-2):1-17.

[7] Rangelow I.W. et al. (2017). Active scanning probes: A versatile toolkit for fast imaging and emerging nanofabrication. *JVST* B **35**(6):10.116.