CO-RESONANT CANTILEVERS FOR MATERIALS RESEARCH AND SENSOR APPLICATIONS

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ABSTRACT

Employing co-resonant coupling in dynamic-mode cantilever MEMS sensors has the potential for a significant increase in sensitivity while maintaining a reliable oscillation detection. However, the resulting complex interplay between the micro- and nanocantilever has to be carefully considered for application-specific sensor design as it impacts all relevant sensor properties, such as linearity, stability and detectivity. Here, an overview of key parameters, their dependence on the strength of co-resonance and resulting consequences for sensor performance is provided.

KEYWORDS

Cantilever sensor, dynamic-mode, co-resonant coupling, sensitivity, stability, linearity

INTRODUCTION

Dynamic mode cantilever sensors are used in a wide variety of applications, from materials research to mass and gas sensing [1,2]. The persisting challenge is the demand for increased sensitivity while at the same time ensuring reliable and robust oscillation detection. Several innovative ideas are studied for that purpose, for example use of higher order bending modes [3,4] or specifically tailored geometries [5].

Within this scope, we are pursuing an approach of co-resonantly coupled cantilevers [6]. The tremendous potential of this concept has been demonstrated experimentally, e.g. by observing magnetization reversal in Heusler-nanoparticles at room temperature which was not possible with cantilever sensors before [7]. In all experimental studies an increase in measurement signal strength and sensitivity by several orders of magnitude was found compared to a single sensitive microcantilever [8]. Furthermore, we have introduced a novel read-out method based on time-scale observation of sensor beating [9].

Despite its potential, common application of the concept is still limited since the co-resonance induces a multitude of complex interdependencies on sensor properties which had not been fully understood until now. While the theoretical basics can be found in [10,11], we here present very recent extensive experimental studies which allow to validate and verify them. For the first time, this enables comprehensive insights and allows to draw conclusions with regard to practical sensor design. In the following, some key aspects are highlighted.

CREATION OF CO-RESONANT STATE

The sensor concept is based on mechanical coupling of two vastly different oscillators (geometry and material properties), where ideally one is very soft and therefore sensitive to external interactions (i.e. nanocantilever) and the other one ensures reliable oscillation detection (i.e. microcantilever) [6]. Co-resonance is introduced by matching the eigenfrequencies of these two beams, either by appropriate geometric design or by lowering the usually much higher eigenfrequency of the nanocantilever through point mass deposition at its free end. Examples of fabricated sensors are depicted in Fig. 1. While any matching degree is possible, the co-resonance becomes strongly evident for eigenfrequency deviations between micro- and nanocantilever in the range of ±20 %.

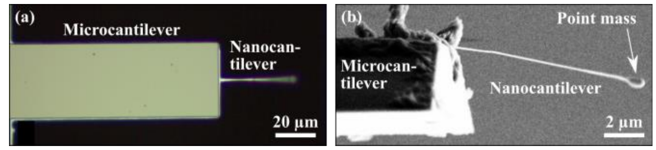

Figure 1: Exemplary co-resonantly coupled sensors: (a) Top view of silicon nitride system with intrinsic eigenfrequency matching (Δf = 1.4 %) by geometry. Dimensions (length (l) x width (w) x thickness (t)): microcantilever = (110 x 40 x 1) µm; nanocantilever = (35 x 1 x 0.1) µm. (b) Side view of silicon microcantilever with carbon nanotube nanocantilever attached by amorphous carbon deposition and eigenfrequency matching by platinum point mass. Dimensions: microcantilever (trapezoidal cross section): l = 105 µm, w_{top} = 15.7 µm, w_{bottom} = 37.2 µm, t = 4.1 µm; nanocantilever (circular cross section): l = 10.7 µm, diameter = 0.1 µm. Please note that only the microcantilever's free end is shown for better visibility.

Table 1: Properties of an experimental co-resonantly coupled sensor made from a silicon microcantilever and a carbon nanotube as depicted in Fig. 1b.

	Microcantilever	*Nanocantilever*
Spring constant	51.6 N/m	0.004 N/m
Quality factor	6540	350
Initial unmatched eigenfreq.	448.32 kHz	1,360 kHz
Adjusted eigenfreq. +10%	Same as initial	493.4 kHz
Adjusted eigenfreq. -1 %	Same as initial	442.4 kHz

CONSEQUENCES FOR SENSOR PERFORMANCE

With reduced eigenfrequency deviation, the amplitude ratio (i.e. amplitude amplification) between the nanocantilever's and microcantilever's free end increases (Fig. 2). While potentially beneficial for some applications, it also means that the nanocantilever can traverse into a non-linear bending regime, chaotic and unstable oscillation and, thus a distorted amplitude response curve (Fig. 3).

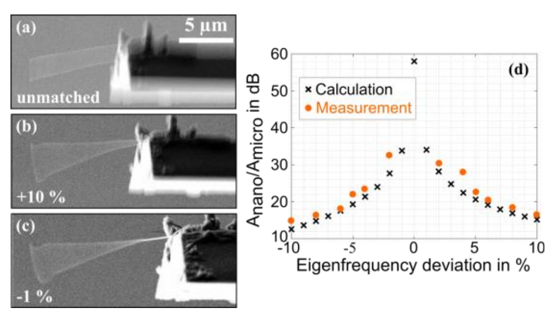

Figure 2: Amplitude amplification for the experimental sensor from Fig. 1b. (a) - (c) Exemplary SEM images of the resulting oscillation envelope for different matching states at an excitation frequency of 448 kHz (+10% means that the nanocantilever's eigenfrequency is 10% above that of the microcantilever). Excitation voltages applied to shaker piezo plate: (a) 200 mV, (b) 50 mV, (c) 20 mV. (d) Measured and calculated amplitude amplification curve based on the initial properties given in Tab. 1. Please note that there is no experimental data available for ±1% and 0% due to undetectable microcantilever amplitude in SEM images.

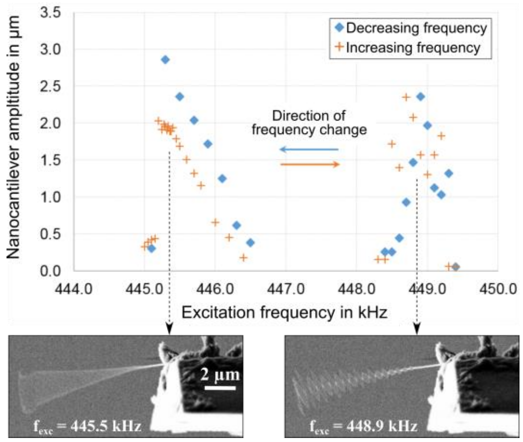

Figure 3: Measured amplitude response curve obtained from SEM images for the experimental sensor with -1% eigenfrequency deviation (properties see Fig. 1b and Tab. 1). The left peak exhibits a Duffing *distortion and the right peak chaotic oscillation behavior of the nanocantilever as visible in the corresponding SEM images.*

Hence, to ensure sensor **stability**, the driving amplitude could be reduced, resulting in a smaller microcantilever amplitude and potentially decreased signal-to-noise ratio. Another solution would be the reduction of eigenfrequency matching, i.e. reduced co-resonant state, but with the drawback of diminished sensitivity.

Sensor **sensitivity** and **detectivity** have an opposing dependency on the degree of eigenfrequency deviation**.** Hence, while sensitivity is large for small deviations, detectivity is reduced [10]. This is due to the fact that the nanocantilever's properties provide a larger fraction of the coupled system's properties for closely matched eigenfrequencies. While beneficial in terms of sensitivity, it can be disadvantageous for detectivity since the nanocantilever often has a (much) lower quality factor than the microcantilever. This results in a significantly smaller quality factor of the measured main resonance peak (Fig. 4). A solution would be to carefully consider material choice for the nanocantilever as well as the conditions under which the sensor is to be used (e.g. vacuum, air, liquid).

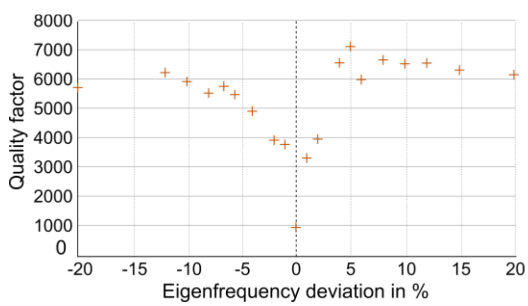

Figure 4: Quality factor of main resonance peak in dependence on eigenfrequency deviation for sensor in Fig. 1b obtained by fitting of measured amplitude response curves with a Lorentzian *peak function.*

SUMMARY

The strength of co-resonance has an impact on many different aspects of the coupled system's behavior and their interplay, and all of them need to be carefully considered and weighted for application-specific sensor design. With the above described new experimental studies, the previous theoretical modelling has been validated and confirmed. Thereby, we enable reliable predictions of sensor performance and derivation of necessary properties to achieve a desired behavior (e.g. sensitivity, amplitude amplification). This provides a practical basis for design of highly sensitive cantilever sensors with reliable oscillation detection which can for example be employed to study properties of novel nanomaterials, previously inaccessible by this technique. Furthermore, since the sensitivity is mainly defined by the nanocantilever properties, the co-resonant concept itself can enable self-sensing/self-actuation on the microcantilever and, hence extend use cases of these types of sensors.

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