ORIGIN OF THE RESPONSE OF NANOMECHANICAL RESONATORS TO BACTERIA ADSORPTION

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By performing experiments of adsorption of the bacteria *Escherichia coli* on singly clamped microcantilevers, we demonstrate that the effect of the added mass is not the only and may not be the main origin of the response of these sensors. The experiments show that the magnitude and sign of resonance frequency shift both depend critically on the distribution of the adsorbed bacterial cells on the cantilever. We relate this behavior to the added mass that shifts the resonance to lower frequencies and the higher effective flexural rigidity of the cantilever due to the bacteria stiffness that shifts the resonance to higher frequencies. Both effects can be uncoupled by positioning the cells where each effect dominates, near the free cantilever end for measuring the added mass or near the clamping for measuring the increase of flexural rigidity.

We propose a model that accounts for the mechanical properties of the attached bacteria that increase the stiffness of the cantilever. We model our cantilever as an Euler-Bernoulli beam, in which both the mass per unit length and the flexural rigidity are dependent on the longitudinal position

To calculate the resonance frequency we have applied Rayleigh's approximation. This method deduces the resonance frequencies by performing an energy-work balance and assuming that the eigenmode shapes are not substantially changed by the adsorbed bacteria resonance frequency is calculated as

$$\omega_n^2 = \frac{\int_0^L D(x)\left(\frac{\partial^2 u_n(x)}{\partial x^2}\right)^2 dx}{\rho WT\int_0^L \left(1+\frac{\rho_a}{\rho}\frac{T_a(x)}{T}\right)u_n^2(x)dx}$$

We have applied this equation to estimate the first mode resonance frequency shift due to the increase of mass and flexural rigidity induced by the deposited bacteria. We model the adsorbed bacteria as a homogeneous and uniform disk with a diameter of 100 μm that contains 4200 bacteria cells. The bacterium mass is 665 fg, and the biolayer height is 840 nm, smaller than the bacterium height of about 1 μm, to reflect that the adsorbed bacteria are not densely packed in the experiments. Young's modulus of 1.3 GPa was chosen in order to mimic the experimental results. This value is similar to those obtained by atomic force microscopy measurements in dried bacteria. The second figure shows the calculated frequency shift versus the adsorption position along the cantilever due to the added mass (dashed line), the change of flexural rigidity (dashed line), and both effects (solid line). The experimental values of the resonance frequency shift obtained from the cantilevers shown in the first figure are also included (symbols). The theory shows a good agreement with the experimental data indicating the consistency of the presented model. The added mass of the adsorbed bacteria produces a negative resonance frequency shift whose magnitude varies from approximately null for the adsorption near the clamping to maximal for the adsorption

In conclusion, we have demonstrated that the response of nanomechanical resonators to bacteria adsorption does not only depend on the added mass, but also on the stiffness of the bacterial cells. Both effects can be uncoupled by positioning the bacterial cells where each effect dominates, near the free cantilever end for measuring the added mass or near the clamping for measuring the increase of flexural rigidity. Both geometries allow sensitive bacteria detection of about 0.1 Hz per bacterium. This sensitivity can be easily enhanced by at least one order of magnitude by using higher vibration modes or by scaling down the cantilever size. The results of this work can be generalized to the adsorption of any molecule. In addition, the effect of the mechanical properties of the adsorbed molecules will become increasingly important as the size of the resonators is decreased towards the nanoscale.

References:

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