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The dynamics of viscoelastic layered systems studied by surface acoustic wave (SAW) sensors operated in a liquid phase

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Abstract

We theoretically study a three-layer continuum model of a surface acoustic wave sensor where the two overlayers are allowed to be viscoelastic. This case is particularly important in biosensing, where soft materials submerged in fluids are commonplace. From the general dispersion equation, we calculate the phase velocity shift and the wave attenuation. We show that there is a viscoelastic coupling between the overlayers which results in unintuitive behavior, e.g., the addition of viscous loading to a soft-film sensor can reduce the attenuation.

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Keywords: Surface acoustic waves, acoustic sensors, viscoelasticity, sensor modeling

1. Main text

Acoustic sensors have been used for bio-sensing in liquid conditions. A typical bio-sensing application is the probing of biological layers formed by the deposition of e.g., proteins, lipid vesicles, or cells, from a liquid onto a sensing surface [1]. The principle behind acoustic sensors is that the deposition of mass onto the surface of an oscillator changes its vibrational properties. For a quartz crystal microbalance (QCM), there is a shift in the resonance frequency and, for viscous deposits, a dissipation of vibrational energy. Analogously, for a surface

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acoustic wave (SAW) sensor, the phase velocity of the waves is shifted and the waves might attenuate due to viscous losses [2]. Measuring the velocity shift and the attenuation can provide information about the nature of the deposited mass, allowing for ultra-sensitive mass measurements or determination of material parameters, such as shear modulus or viscosity.

However, a correct interpretation of the measurement data rests on a theoretical basis, and e.g., operating an acoustic sensor in a liquid and neglecting the viscoelastic coupling of the liquid and the deposit softness (viscoelasticity) can lead to an underestimation of the deposited mass, a "missing mass" effect [3]. Consideration of viscoelastic coupling is especially important in biological applications, where soft matter is commonplace and sensor measurements are often carried out in liquid-phase environments.

We consider a theoretical model of a SAW sensor consisting of two viscoelastic layers on top of an infinitely deep elastic substrate. The SAWs are shear-horizontally polarized. We use continuum viscoelasticity theory to derive a dispersion equation, and using this we can numerically calculate and plot the phase velocity shift and wave attenuation for different cases, as well as derive analytical expressions for these quantities in the limiting case of the first overlayer being acoustically thin and the top being semi-infinite (e.g., a film in a bulk fluid). We perform numerical calculations for a range of film thicknesses, comparing rigid (elastic) and soft (viscoelastic) films immersed in different fluids. Compared to rigid films, soft films can react qualitatively different to a change in the fluid properties; e.g., for soft films, increasing the fluid viscosity can actually *reduce* the attenuation and mass sensitivity, while for a rigid film, both are increased (see fig. 1). It is therefore shown that the simple picture of mass loading inducing a velocity shift and viscous loading inducing attenuation is not correct for soft materials.

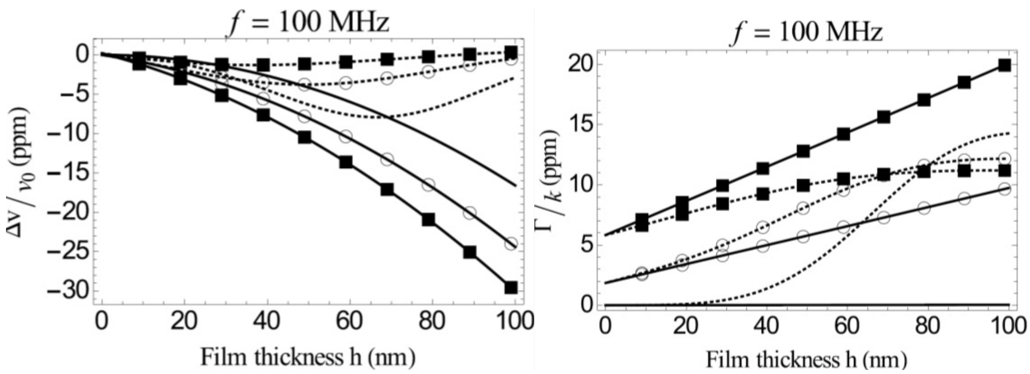

Fig 1. Numerically calculated phase velocity shift (left) and scaled attenuation coefficient (right) [parts per million, ppm] for quartz covered by two different films immersed in three different fluids, vs film thickness h (nm). Rigid film (solid lines, PMMA) or soft film (dashed lines, PLL-PGA) immersed in a water/glycerol mixture (■), water (○), or air (no markers).

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