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Optimizing a Phase-Locked Loop for Scanning Probe Microscopy

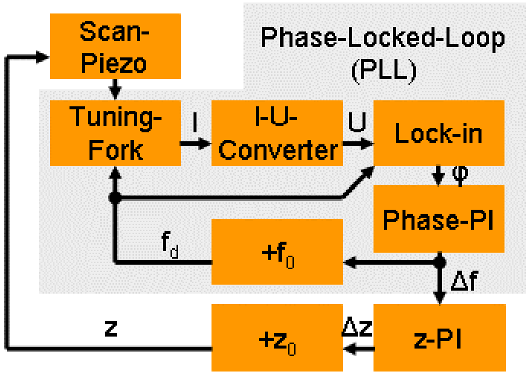
A. Gildemeister, T. Ihn, K. Ensslin, **J. Rychen**[1], T. Vancura[1]
Laboratory of Solid State Physics, ETH Zürich, Switzerland
[1]Nanonis GmbH, Zürich, Switzerland
gildemeister@phys.ethz.ch

Phase-Locked Loops (PLL) [1,2] are increasingly used to control the sensor frequency in scanning probe microscopes. They allow increasing the measurement bandwidth beyond the sensor's own characteristic bandwidth. We present a detailed analysis of a PLL-control using linear response theory [3] along with corresponding measurements on a digital Nanonis Oscillation Controller [4]. We provide hands-on rules for optimizing PLL parameters with regard to both bandwidth and noise together with an automated setup from Nanonis.

The analysis applies to all phase-sensitive sensors. In particular, we use a tuning fork (TF) driven at resonance. The phase φ of the transmitted current is very sensitive to shifts of the resonance frequency caused by force gradients. We measure φ with an integrated digital lock-in detector. A proportional and integral filter (PI) completes the PLL that always drives the TF at resonance. We analyze the PLL's behavior in the frequency domain in order to understand how quickly it can react to a step on the surface.

The PLL has three parameters. The sensor's characteristic frequency f_c is given by its resonance frequency f_{res} and the quality factor Q with $f_c = f_{res}/2Q$. A proportionality constant P and a time constant T can be set for the PI. The highest bandwidth without losing stability is achieved for $T=(2\pi f_c)^{-1}$. Then the PLL constitutes a first order low-pass filter with bandwidth P and noise proportional to P.

An additional z-feedback loop is required for height control. It keeps the frequency shift constant by controlling the distance z between sample and sensor. The z-PI has two parameters, T_z and P_z. It is optimized for $T_z=(2\pi P)^{-1}$ and has a bandwidth of $\beta P P_z$, where β is given by the tip-sample interaction. The noise on z is proportional to PP_z.



In our setup the I-U-converter (IUC) is the dominant source of noise which is then only transferred by the PLL. Thus, if the IUC noise and the sensor properties are known, all parameters are determined for a given acceptable noise on z. The bandwidth can be calculated from the parameters and the maximum scanning speed is determined.

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