NONLINEAR SPATIO-TEMPORAL DYNAMICS AND STABILITY OF THE SCAN PROCESS IN NON-CONTACT ATOMIC FORCE MICROSCOPY

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Summary We investigate the nonlinear spatio-temporal dynamics of the scan process in non-contact atomic force microscopy. The investigation is based on a consistent derivation of an initial-boundary-value problem for a vibrating micro-cantilever that incorporates internal and combination resonances between in-plane and transverse bending modes with the fundamental torsion mode. The coupled problem is analysed asymptotically and numerically corresponding to weak and strongly nonlinear regimes, respectively. Stability analysis of the resulting slowly varying evolution equations yield conditions for coupled modal energy transfer that facilitate simultaneous imaging and force detection.

The atomic force microscope (AFM) has become a standard instrument in nanotechnology for imaging of surfaces at the micro- and nanometer scales. The highest lateral resolution that can be obtained in AFM sampling is via dynamic mode operation, where the cantilever oscillates near a target sample surface. If one uses the amplitude change as the control signal, it is possible to measure the sample topography with high vertical and lateral resolution. Other techniques have also been developed to obtain information about tip-sample interactions. For example, the resonant frequency of the cantilever can be measured as a function of the tip-sample separation, from which the tip-sample interaction force can be obtained [1]. However, these additional measurements can only be performed through a subsequent characterization after scanning of surface topography. Recently, bimodal excitation of the first and second AFM cantilever bending modes has enabled higher force sensitivity and compositional contrast where the first mode was used to record sample topography and the second mode was used to explore tip-sample forces [2]. Triple frequency excitation has also enabled simultaneous sampling of topography and complementary surface properties [3]. Furthermore, hybrid AFM cantilever designs with two cross-sections [4] have been employed to facilitate access to higher oscillation bending modes and demonstrated access to the fundamental torsional mode. Sahin et al. [5] introduced an approach using specific cantilevers where the normal and torsional oscillations of the cantilever are employed for imaging and spectroscopy, respectively. The simultaneous excitation of both in-plane bending and torsional modes was obtained by off-center placement of the AFM tip where the torsional natural frequency was close to that of the third in-plane bending mode. In this approach the surface structure was obtained from the normal vibration scanned, whereas the tip-sample interaction is measured through a Fourier analysis of the torsional cantilever oscillation. While the experimental results of multiple mode excitation and internal resonances between the bending and torsional modes have shown that the basic concept of simultaneous imaging and force detection is feasible, the accuracy of force estimation is limited to slow scan operation that cannot be analyzed by traditional lumped mass models that do not incorporate the AFM horizontal raster motion.

Thus, the objective of this investigation is to derive and theoretically analyze a consistent continuum model for spatio-temporal AFM operation incorporating where direct excitation of a vertical bending mode can induce response of the lateral bending and fundamental torsional modes via internal and combination resonances. We employ the extended Hamilton's principle to derive the AFM initial-boundary-value problem (Fig.1-left) which consists of four partial differential equations for longitudinal deformation, vertical and transverse bending and torsion. The coupled fields incorporate viscoelastic damping and the vertical bending includes a localized atomic interaction model for the non-contact AFM [6]. The coupled elastic fields are reduced to a five mode geometrically nonlinear dynamical system that includes three coupled vertical bending modes with both lateral bending and a torsion mode.

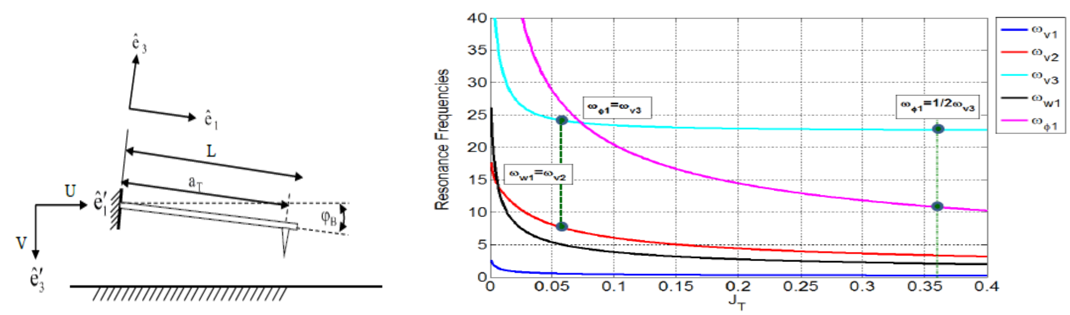

Figure 1: Definition sketch (left) and conditions for internal resonances (right)

Analysis of the linear boundary-value problem yields several combinations for internal resonances (Figure 1-right) such as a 2:1 resonance between the fundamental torsion and second bending mode, or a 3:3:1 internal resonance between the torsion and the third and second bending mode.

Stability analysis of the equilibrium configuration yields a homoclinic phase-plane (Figure 2-left) which when perturbed reveals a 'jump-to-contact' stability map that governs the parameter space for safe non-contact AFM operation (below the escape threshold) .

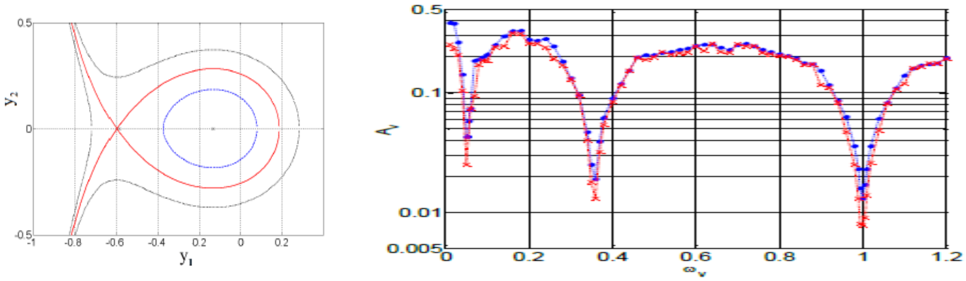

Figure 2: Hamiltonian phase-plane (left) separating periodic (blue) from tapping (black) solutions, and a 'jump-to-contact' stability map (right) for conditions near a 3:1 internal resonance.

A combined multiple-scales asymptotic analysis of the weakly nonlinear system reveals internal resonances culminating with periodic and quasiperiodic energy transfer due to a 3:1 internal resonance between the second and third bending modes (Figure 3-left) and due to a 2:1 internal resonance between the second bending and fundamental torsion modes (Figure 3-right).

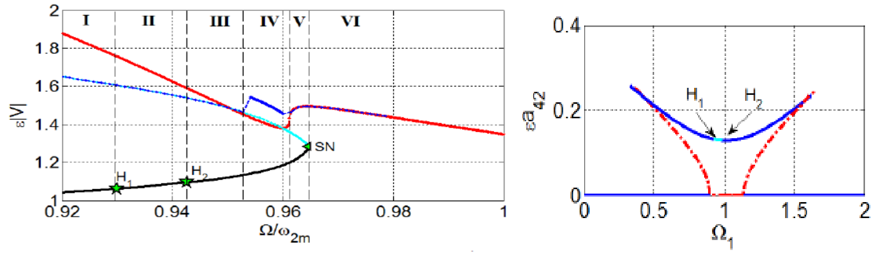

Figure 3: Frequency response diagrams of the second bending mode. Internal resonances: 3:1 (left), and 2:1 (right) where SN and H denote saddle-node and Hopf bifurcations respectively.

The numerical analysis of the coupled nonlinear dynamical system reveals within the domain existence of bi-stable periodic solutions (not shown), complex quasiperiodic solutions (Figure 4-left) and non-stationary chaotic like solutions that are an outcome of orbital loss of stability of a quasiperiodic torus.

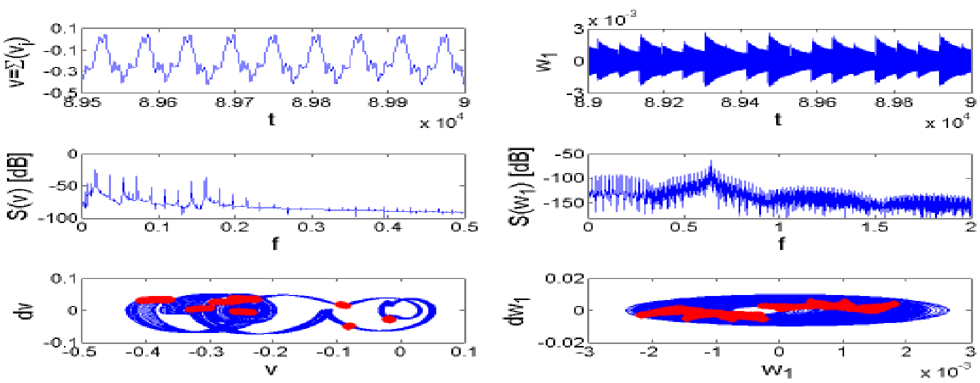

Figure 4: Quasiperiodc (left) and non-stationary (right) response of the AFM cantilever near a 2:1 internal resonance

The novelty of this investigation is that conditions for internal resonance based sensing of the non-contacting AFM are accurately predicted by a consistent analysis of a theoretical nonlinear continuum based spatio-temporal model. Robustness of these predictions will be further analysed for hard excitation incorporating the effects of nonlinear damping [7].

References

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