INVESTIGATION OF THE DYNAMICS OF COUPLED CANTILEVER ARRAYS ON A MICRO AND MACRO SCALE WITH APPLICATIONS TO AFM

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Since the invention of atomic force microscopy (AFM) researchers have been trying to increase imaging speed. One method is to bring multiple cantilever probes together in close proximity to form an array. By using each probe independently, multiple points on a sample can be imaged simultaneously. AFM arrays have been developed and produced by the Rangelow research group under the PRONANO project at Technische Universität Ilmenau [1]. These arrays are fabricated from multi-layer silicon beams and have bimetallic heater actuators and piezo-resistive sensors incorporated into each probe, allowing for individual actuation and sensing (Figure 1). Due to the close proximity of the cantilevers, the system response exhibits coupling phenomena (mechanical, electrical, thermal and fluidic). The way this coupling affects the dynamics of each beam and the system as a whole is not fully understood.

There is limited knowledge in the literature pertaining to the nature of coupled cantilevers in close proximity with individual actuation and sensing, influenced by nonlinear tip-sample interaction forces. Mathematical models have been created to describe coupled AFM arrays ([2], [3]) and there are a few examples of control algorithms ([4], [5]), however, these models and algorithms are largely developed from a theoretical perspective and have not been applied to a working AFM array. To the best of the author's knowledge, there is no example in the literature of a detailed experimental investigation of the dynamics of a coupled AFM array. This lack of understanding is currently limiting the applicability of the technology. The authors plan to approach the problem from a combined theoretical and experimental perspective to gain a deeper understanding of the PRONANO array dynamics and use this knowledge to develop feasible imaging technology.

We present an experimental investigation of the dynamics of a PRONANO array (Figure 1) and discuss the coupling present in the system and how it affects the response of each cantilever to various inputs. In addition, we present a novel research tool in the form of a macro scale set up. A major obstacle preventing the full understanding of AFM arrays dynamics is the difficultly in observing the system response and how it is affected by changes in design parameters. An equivalent macro scale system that mimics the mechanics of a PRONANO array is proposed as a way to easily observe the system response and vary key parameters (Including individual beam dimensions and coupling strength). We present initial experimental results of the proposed set up.

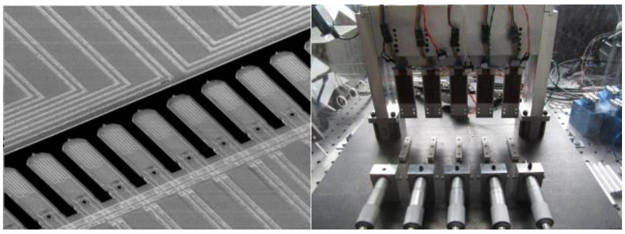

Figure 1: SEM image of a PRONANO array (left) [1], and the proposed equivalent macro scale set up (right).

We also present a mathematical model of a coupled AFM array (1). P, A, c, E, I, T and d_0 are constants, w_n is the deflection of beam n, F is a forcing term and k is the mechanical coupling between cantilevers. This model is developed from a continuum mechanics approach using Euler Bernoulli beam theory. Individual actuation and nonlinear tip-sample interaction forces are incorporated into each beam.

$$\begin{aligned}\rho A\ddot{w}_n + c\dot{w}_n + EI{w_n}^{iv} + 2kw_n - kw_{n-1}\\ -kw_{n+1} = \frac{T}{\left(d_0 - w_n(L)\right)^2} + F\end{aligned} \tag{1}$$

The model has been used to identify suitable parameters for the construction of the macro scale test set up (cantilever dimensions, coupling strength and tip-sample interaction force strength) and to predict how these parameters will affect the response. The experimental setup itself was designed based on a PRONANO array. The macro scale array consists of 5 beams fabricated from aluminium sheet (Figure 1). Each beam incorporates a piezo film actuator and resistive Wheatstone bridge sensor. The system was found to exhibit strong mechanical coupling, producing 5 distinct mode shapes as shown in Figure

2 (modes 1 and 2 are very close). Bringing a magnet in close proximity to the tip of a single cantilever was found to reduce the resonance frequency of each mode at each beam in the array. By bringing a magnet towards the tip of cantilever one from a distance of 1.2mm to a distance of 0.6mm, the frequency of mode 3 decreased by 1.8% whilst the frequency of mode 4 decreased by only 0.2%.

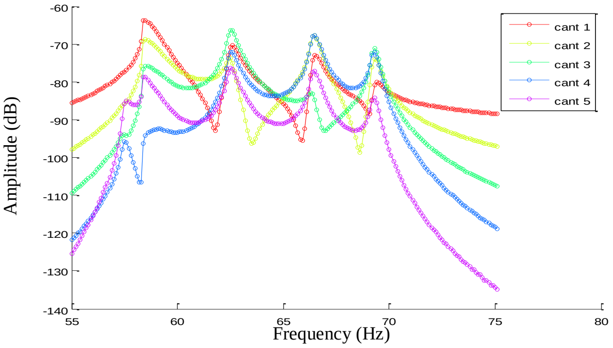

Figure 2: Frequency response of a 5 beam macro array. The response was produced by actuating cantilever one only

The PRONANO array consisted of 17 beams with actuation provided to 4 beams at a time using the bimetallic heaters. The tip displacement and velocity of each beam was measured using a laser vibrometer. It was found that each beam had its own distinct eigenfrequency (see impulse response in Figure 3. Using frequency sweeps, it was determined that the difference in eigenfrequencies and low strength of the mechanical coupling resulted in no synchronous behaviour between beams and hence specific mode shapes could not be found.

Despite the lack of mode shapes, a coupling was found to alter output amplitude through the response of neighbouring beams. Actuating beams 10 and 11 at resonance increased the output amplitude of beam 9 by 2.1% at resonance, whilst actuating beams 9 and 10 at resonance decreased the output amplitude of beam 11 by 3.8% at resonance. This is most likely due to the differences in eigenfrequencies between beams 9, 10 and 11. It was found that altering the amplitude and phase did not significantly affect the resonance frequency of neighbouring beams.

Applying a DC offset to a beam was found to cause a noticeable offset to its neighbor. Applying a 40nm offset to beam 9 using the heater actuator created a 3nm offset at beam 10. Applying a DC offset did not significantly alter the amplitude or resonant frequency of neighbouring beams.

Our mathematical model and macro test rig have demonstrated the significant influence synchronous behaviour has on AFM array response, but it is not yet known under what conditions such synchronous behaviour is produced on the micro scale. The micro experimental results show that coupling has a greater influence on the amplitude and DC offset of each beam than on frequency and that manufacturing tolerances play a major role (as was shown, both an increase and a decrease in amplitude was measured depending on the eigenfrequencies of the specific beams excited). A similar result could not be found in the literature and must be investigated further. The outlook for the macro scale is to understand how key system parameters affect the level of coupling in the system and what parameter ratios cause the creation /destruction of distinct array modes.

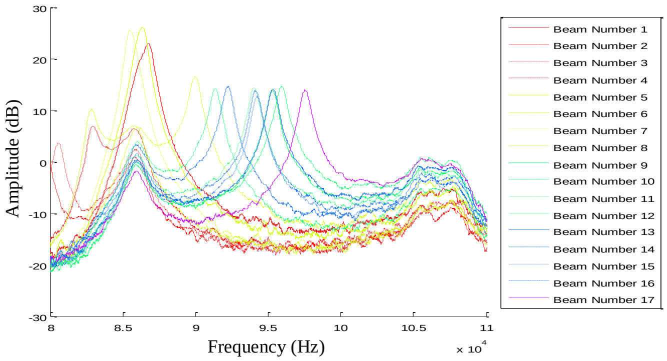

Figure 3: Impulse response of a 17 beam micro cantilever array using a base mounted piezo actuator.

The ultimate goal will be to create control algorithms that can accurately and reliably image a surface with multiple probes simultaneously in the presence of coupling interactions using any manufactured PRONANO array.

REFERENCES:

[1] Y. Sarov, T. Ivanov, A. Frank, J. P. Zöllner, N. Nikolov, and I. W. Rangelow, "Realization of cantilever arrays for parallel proximity imaging," *Journal of Physics: Conference Series*, vol. 253, p. 012050, 2010.

[2] M. Napoli, W. Zhang, K. L. Turner, and B. Bamieh, "Characterization of electrostatically coupled microcantilevers," *Journal of Microelectromechanical Systems*, vol. 14, pp. 295-304, 2005.

[3] M. Lenczner, "Multiscale model for atomic force microscope array mechanical behavior," *Applied Physics Letters*, vol. 90, p. 091908, 2007.

[4] H. Hui, Y. Yakoubi, M. Lenczner, and N. Ratier, "Semi-decentralized approximation of a LQR-based controller for a one-dimensional cantilever array," in *18th IFAC World Congress*, ed, 2011.

[5] M. Dahleh, B. Bamieh, and M. Napoli, "Optimal Control of Arrays of Microcantilevers," in *IEEE conference on Decision and Control* vol. 121, ed, 1999, pp. 2077-2082.