Modal actuation for high speed piezoelectric positioning

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Abstract

A common problem in the design of feedback controlled piezoelectrically actuated positioning systems are resonant modes that are close to the controller bandwidth. The control problem is particularly complicated if model-uncertainty due to variation of these modes has to be taken into account. A possible solution to this problem is the application of modal actuation. In this approach the electrodes of the piezoelectric actuator are modified in such a way that the motion on the free end of the actuator is based only on the excitation of a specific subset of resonant modes. In this contribution the tuning of modal actuators to account for load variations is investigated and the in situ tuning approach is compared to a robustness approach where the modal actuator is tuned to match a worst case load variation.

1 Introduction

Piezoelectric tube actuators are widely used in systems requiring positioning with nanometer precision. An example of such a system is the atomic force microscope (AFM) [1] where piezoelectric actuation is used to regulate probe-sample interaction. In general, the bandwidth of piezoelectrically actuated systems is optimized by designing a feedback control system taking into account the low order resonant modes of the actuator [2]. As an alternative to damping resonant modes through feedback control, the excitation of these modes can be avoided by the application of modal actuation [3]. In this approach the forces introduced in the piezoelectric material by the piezoelectric effect are redistributed to fit a specific modes shape. In [3] this effect is achieved by modification of the applied electric field by shaping the live electrode. The advantage of this approach is that a single voltage can be used to drive the actuator. A second way of achieving modal actuation is to divide the live electrode into discrete sections and vary the amplitude of the voltages applied to the individual sections. The advantage of this approach is that in situ retuning of the modal filter is possible by varying the voltages applied to the sections. In systems with changing load conditions such as atomic force microscopes this may lead to improved performance. In this paper the influence of changing load conditions on modal actuators is investigated using a case study based on finite element analysis of a typical AFM setup.

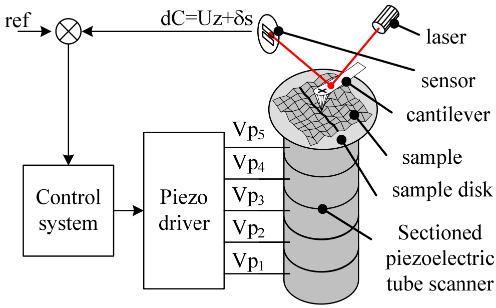

Figure 1: Layout of the AFM vertical axis feedback loop including modal actuation.

2 Modal actuation

The system under consideration is a 60 mm long piezoelectric tube actuator with a radius of 5 mm was loaded by a steel disk with radius 6 mm and thickness 0.76 mm. The frequency response functions are obtained using a finite element model based on 3d solid elements. A mesh of 80x95x2 elements in axial, circumferential and radial direction proved to be sufficient to avoid stiffening effects such as shear locking and allow correct simulation of high order modes.

Modal actuators based on sectioned electrodes can be designed by obtaining the harmonic response of system to voltages applied to each input. As can be seen in Figure 2, the relative ordering of the resonant modes and the anti resonances cause phase differences between the harmonic responses of each section. By tuning the gains it is possible to balance the contribution of each section to the output of the system in such a way that the net contribution of a mode to the output is zero. This can be done for a set of modes causing the system to resonate in only a single mode. The result is shown in the lower right frame in Figure 2. It is clear that the excitation of modes 2-5 is significantly reduced. The excitation of the high order modes is due to the limited set of sections which does not allow the reduction of modes with more complex mode shapes. A side effect of the modal actuation is the reduction in static gain which is caused by the attenuation of the section voltages.

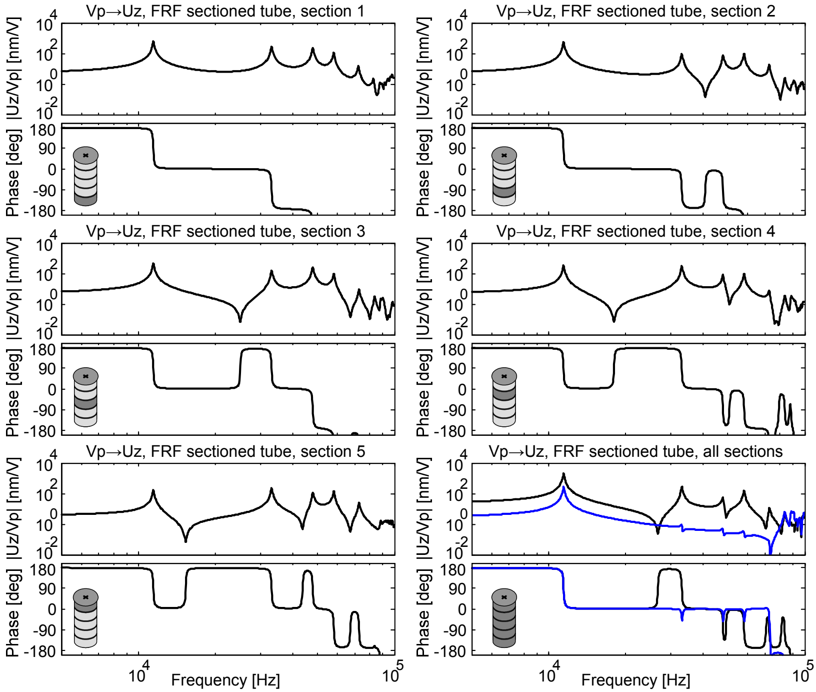

Figure 2: Frequency response functions of sections 1-5 and full actuator (right-bottom) and modal actuator tuned to cancel the second mode (blue).

3 Modal actuation in systems with changing load conditions

Modal actuators tuned for a specific load case are sensitive to changing load conditions. If this load can be considered rigid, the first and second mode shift to lower frequencies and the ordering of resonant modes and anti-resonances is unaffected as is shown in Figure 3. In the case of a non-rigid load such as a thin disk, an additional resonant mode in the same frequency range as the low order axial tube modes appears. For relatively thick disks the frequency where this bending mode occurs is at a much higher frequency allowing the load to be treated as rigid. If the load conditions change after a modal actuator is tuned, the modes that are not excited in the nominal case may reappear see Figure 4 (left). Modal actuators that rely on a fixed, single-section electrode layout can not be changed and are therefore less suitable in applications with changing load conditions. In the case of an in-situ tuned modal actuator, adaptation is possible regardless of changes in the ordering between resonant modes and anti-resonances caused by changes in load flexibility as is shown in Figure 4 (right). An additional benefit of in situ tuning is that the static range can be optimized in a specific load case. The results shown in Figure 4 indicate that modal actuation based on in situ tuning leads to a higher performance than the robustness approach, where a single, fixed gain is tuned to fit load variations.

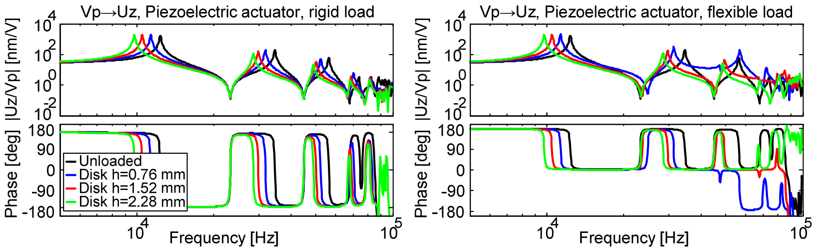

Figure 3: The influence of a rigid (left) and flexible (right) load on the dynamics of the vertical axis of a 60x10 mm (LxD) tube actuator.

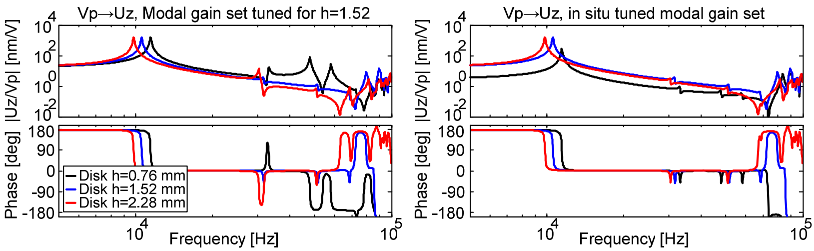

Figure 4: Modal actuation for varying load conditions by tuning in the in the case of an average disk thickness (1.52 mm) and by in-situ tuning (right).

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