Dissecting the dynamic response of an ultra-fast actuated mirror

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Abstract
Piezo-electric elements are widely used to design dynamic actuators. In such devices, the dynamic performance is not only determined by the piezo element itself but also by the packaging and mounting conditions. Here, we used SmarAct's **PICO**SCAN Vibrometer to directly visualize the vibrational modes of the different components of an ultra-fast actuated mirror. This dissection of the dynamic response allows to attribute particular resonance peaks to specific parts of the assembly. The results can be exploited to control and to improve the design of actuators that operate under challenging dynamic conditions.

1. INTRODUCTION

In a minimal design an actuator solely consists of a piezo-electric element that can be set in motion at the desired frequency and amplitude to move an object. In this case the performance depends largely on that of the used piezo element. In most applications however, the piezo is mounted in an enclosure to protect it from the environment and for safety reasons. Because each component of the enclosure will contribute to the overall dynamic response, the performance of such an assembly will be compromised.
Finite element analysis can help to predict the influence of the enclosure on the dynamic behavior. Nevertheless, production tolerances and the exact mounting stresses are difficult to include and will lead to inaccuracies in the simulations. As a consequence, the actual measurement of vibrations remains essential to properly characterize the performance of actuator assemblies.
Here, we employed SmarAct's **PICO**SCAN Vibrometer to directly measure and visualize mechanical resonance modes of an ultra-fast actuated mirror, which consisted of a mounted piezo that was covered by a mirror. Such actuated mirrors are used for the precise control of optical paths in optical instruments such as microscopes and interferometers. To investigate the role of the different components, we measured the vibrations on both the top and the bottom surfaces of the complete assembly and compared these with the response of the bare piezo when this was mechanically disconnected from its mount. The results emphasize the impact of the enclosure (mount and mirror) on the dynamic behavior of the whole assembly.

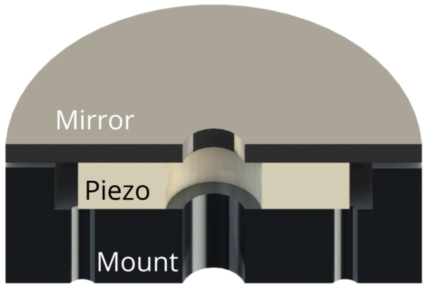

Figure 1. *Cross-sectional view of the ultra-fast actuated mirror. The ring-shaped piezo element is glued in the cup-shaped titanium mount and covered by a polished titanium mirror. The actuation of the piezo brings the mirror in motion.*

2. METHODS

The experiments were performed on a standard **PICO**SCAN Vibrometer. The ultra-fast actuated mirror consisted of a ring-shaped piezo-electric element with an outer diameter of about 8 mm and an aperture of 3 mm. The unloaded resonance frequency, as provided by the manufacturer, exceeded 500 kHz. The piezo element was glued in a cup-shaped titanium mount and covered by a separate polished titanium mirror (Figure 1). All parts of the actuated mirror assembly contained a central 2 mm diameter aperture. The mount contained two additional apertures of 1 mm diameter for the electrical connections. The whole assembly was immobilized with respect to a stainless steel stage support by a set screw that acted on the side-wall of the mount. To measure the isolated response of the bare piezo element, it was taken out of the enclosure and placed on a thin sheet of polyurethane foam. In this case it was mechanically uncoupled from the support.
The experimental workflow was as follows:

- Record a 13 mm $\times$ 13 mm (200 pixels x 200 pixels) microscopy image of the region of interest using the imaging mode of the **PICO**SCAN Vibrometer.
- Position the interferometer beam near the central aperture of the mirror and use the autofocus option to focus the laser.
- Drive the piezo-electric element with a linear sweep at constant amplitude from 1 kHz to 800 kHz using the function generator of the

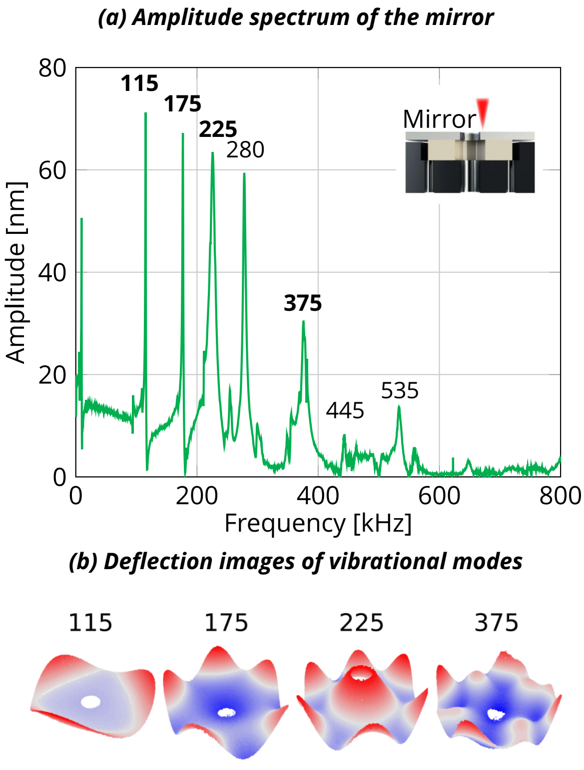

__Figure 2.__ ***(a)*** *Frequency response of the polished titanium mirror. Multiple well-defined resonance peaks are visible.* ***(b)*** *Deflection images of some of the resonant modes (the amplitudes are normalized).*

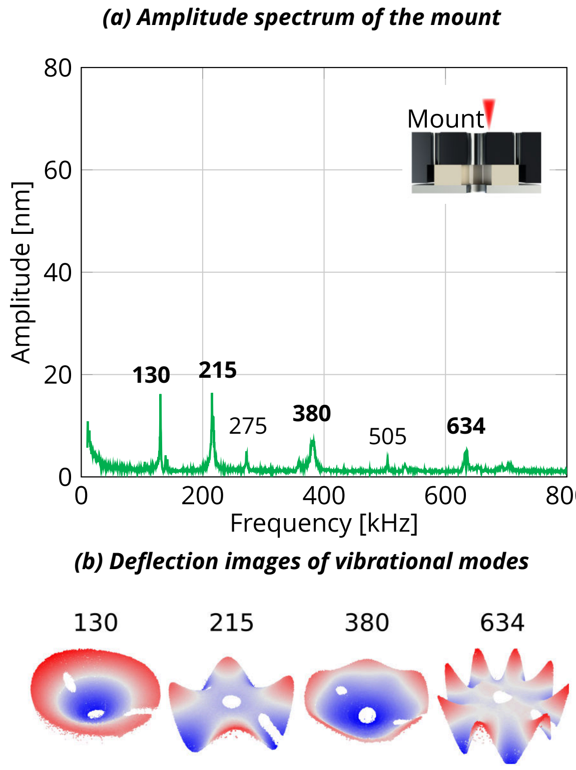

__Figure 3.__ ***(a)*** *Frequency response of the titanium mount.* ***(b)*** *Deflection images of some of the resonant modes (the amplitudes are normalized).*

PICOSCAN Vibrometer. The measured displacements are Fourier transformed to show the amplitude in the frequency domain.

- Select a peak of interest in the amplitude spectrum and actuate the piezo at this frequency.
- Scan the region of 13 mm × 13 mm (500 pixels x 500 pixels). Simultaneously with the microscopy image now also the amplitude and the phase of the oscillations are recorded at each pixel by the digital dual-phase lock-in amplifier. The latter is automatically configured according to the actuating frequency.
- To display the vibrational mode, reconstruct the deflection of the sample at each point of the oscillation cycle by using the standard **PICO**SCAN VIEW software. Basically, for each pixel the deflection d is calculated from the measured amplitude A and phase θ according to $d = A \cdot \cos(\theta)$.

3. RESULTS

Due to the relatively complex geometries and contact boundary conditions, the vibrational modes cannot easily be described by mechanical models. To avoid confusion, we defined the modes by their resonant frequency in kHz rather than by the number and type of nodal lines.

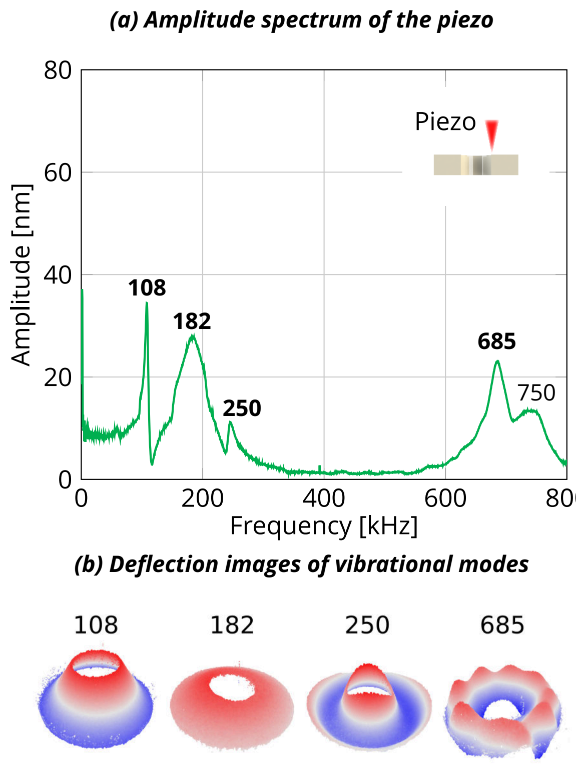

__Figure 4.__ ***(a)*** *Frequency response of the mechanically decoupled piezo.* ***(b)*** *Deflection images of the first four resonant modes (the amplitudes are normalized).*

Dynamic response of the mirror: The vibrations were measured at a single point near the aperture on the top surface of the mirror. They reveal numerous resonance peaks of which many occur at much lower frequencies than the stated resonance frequency of the piezo element (Figure 2a). To visualize the bending modes that are associated to these peaks, a 13 mm $\times$ 13 mm vibration image was recorded at each of the resonance frequencies (see section 2). Figure 2b shows the acquired vibrational modes which gain in complexity at higher frequencies. Because the measurements were performed on the complete assembly the measured dynamics are affected by the mirror, the mount and the piezo element.

Dynamic response of the mount: To measure the vibrations of the mount it was placed upside-down so that the bottom surface could be imaged. The vibrations measured at a single point near the aperture show again multiple resonance peaks but at frequencies that differ from the ones detected for the mirror (Figure 3a). Moreover, the peak amplitudes are in general 3.5 times smaller and appear narrower. Figure 3b shows the vibrational modes of the resonance peaks. The differences between the mirror and the mount likely arise from the respective geometries: the mirror is simply a ring-shaped disc whereas the mount has a more complex cup-like shape and is also heavier.

Dynamic response of the piezo-electric element: In order to investigate the resonance modes from the piezo element itself, this was taken out of the assembly and mechanically decoupled from any support (see section 2). Figure 4a shows the frequency response measured at a single point near the aperture. This spectrum is much smoother than the ones obtained on the mirror and mount and displays fewer and wider resonances peaks at frequencies that differ from the earlier spectra. The imaged vibrational modes are also less complex and likely correspond to the different expansion modes of the ring-shaped piezo element (Figure 4b). Interestingly, multiple of the observed bending modes occur well below the stated resonance frequency of the piezo element.

4. CONCLUSION

SmarAct's **PICO**SCAN Vibrometer was used to characterize the frequency response of an ultra-fast actuated mirror. The measurements show that the dynamic response of the assembled system is much more complex than the behavior of the bare piezo-electric element itself. Vibrations of both the mirror and the mount dominate the overall system performance. By understanding from which parts the various resonance peaks originate will help to systematically improve the design of such high-speed actuators.

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