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Piezo-actuated vibration disturbance mirror for investigating accelerometer-based tip-tilt reconstruction in large telescopes ⋆

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Abstract: The optical performance of large telescopes depends not only on the correction of atmospheric turbulences but also on the suppression of structural vibrations. Nowadays, these disturbances are compensated by Adaptive Optics (AO) systems. Especially for the vibration suppression new control concepts are developed. A well-known method is a state feedback controller. However, for observations with natural faint guide stars the integration time of the wavefront sensor is increased and therefore the bandwidth of the control loop is not sufficient for a fully vibration compensation. Hence, we want to avoid this problem by using an Accelerometer-based Disturbance Feedforward control (DFF), which is independent of the integration time. The vibrations are measured at the relevant telescope mirrors and the tip-tilt modes are reconstructed for the actuator control signals. For investigating the DFF a laboratory setup is built. The setup consists of a classical AO system and additional designed tip-tilt mirrors for simulating and compensating the vibrations. Several accelerometer are mounted at the disturbance mirror. Based on the measured accelerations two position estimators are investigated in order to use them in real telescope applications.

Keywords: vibration measurement, accelerometers, signal reconstruction, estimation algorithms, actuators

1. INTRODUCTION

In the last two decades a new class of Extremely Large Telescope (ELT) has evolved and allows for observations of fainter and more distant objects in the universe than ever before. For reaching the diffraction limit of the telescopes, disturbances such as atmospheric turbulences and structural vibrations up to 50 Hz have to be suppressed. Nowadays, Adaptive Optics (AO) systems are used to compensate both of these disturbances very efficiently. Therefore, a deformable mirror (DM) is added into the optical path, which corrects the disturbances by a conjugated deformation. The mirror is controlled in a feedback loop using a wavefront sensor (WFS).

With the design and construction of large telescopes it was asserted that high frequency vibrations were more dominant than before and could not be compensated by classical AO control loops, see Clenet et al. (2004) and Brix et al. (2008). Hence, new control concepts are considered and a common method is now a state feedback controller, see Petit et al. (2014). However, the bandwidth of an AO loop is also limited by the exposure time of the WFS. For observations with faint natural guide stars the long exposure times are desired to get a better signal to noise ratio (SNR). In that case the bandwidth of the AO loop decreases and the structural vibrations cannot be fully suppressed. Therefore, we investigate a Disturbance Feedforward control (DFF) which is independent of the exposure time. In this concept the vibrations are measured by additional accelerometers at the telescope structure and the mirror displacements (Piston, Tip, Tilt) are reconstructed by established filter techniques. The reconstructed signals are used feedforward for control the AO loop. First investigations on reconstructing structural vibrations from accelerometer measurements were done for the Large Binocular Telescope (LBT) by Böhm et al. (2014) and concerning tip-tilt for the upcoming Multi-AO Imaging Camera for Deep Observations (MICADO) in the European Extremely Large Telescope (E-ELT) by Keck et al. (2012). A schematic view of the AO control system extended by the DFF is depicted in Fig. 1.

For evaluating the performance of the DFF in MICADO a laboratory setup is developed, which consists of a classical AO system and an additional tip-tilt disturbance and compensation mirror. The disturbance mirror is used to emulate the vibrations of large telescopes. Furthermore the mirror contains accelerometers to investigate the reconstruction algorithms for the tip-tilt modes. In this paper,

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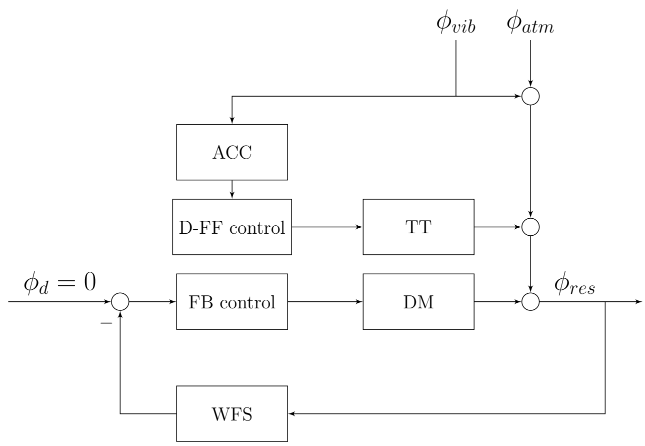

Fig. 1. Classical AO system with an additional disturbance feedforward controller.

we first describe the design of the disturbance mirror. Subsequently we present two reconstruction algorithms and discuss the respective laboratory setup.

2. DISTURBANCE MIRROR DESIGN

Our laboratory setup aims at reproducing the classical optical AO loop of large telescopes, including a tip-tilt disturbance and compensation mirror. The light is collimated by a lens and guided through an aperture to generate a plane wavefront. After that, the light is reflected at the vibration disturbance mirror, which can induce a tip-tilt and piston mode to the plane wavefront. The light is reflected at the compensation mirror, that is fed feedforward with the reconstructed modes. An internal position control is used to set these desired modes. Finally the light passes through an optical system to a deformable mirror with 52 actuators. The reflected light is detected by a Shack-Hartmann wavefront sensor to calculate the control signals for the DM, see Fig. 2.

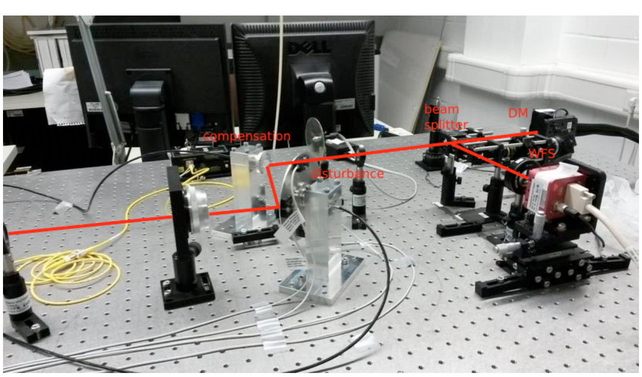

Fig. 2. Overview of the laboratory setup.

The disturbance mirror is used to generate vibrations in the AO system similar to those seen at extremely large telescopes. Furthermore, the vibrations are measured with additional accelerometers that are required for calculating the DFF. The requirements for the disturbance mirror were adjusted to the vibrations in the MICADO instrument. Vibrations with an amplitude range of around 0 nrad...40 nrad (0 mas...200 mas) and a frequency range up to 20 Hz are expected to contribute to the inaccuracy of MICADO at the E-ELT, see Sedghi et al. (2010). Moreover, the diffraction limit of MICADO is around 2 nrad (10 mas) for an observational wavelength of 1.65 μm. The residual after vibration mitigation needs to be clearly smaller than the diffraction limit. In our lab setup we use a HeNe laser (630 nm) and an aperture of 3.5 cm. Hence, we get a diffraction limit around 0.93 μrad (4.5 arcsec), because the limit is proportional to λ/D, whereby λ is the observation wavelength and D the diameter of the aperture. In order to have a comparable setup, we scaled up the vibration requirements. Since we have a factor 20 between diffraction limit and expected vibrations at the E-ELT, using of the same ratio for our lab setup yields a range of $\pm 20\,\mu$rad for the tip-tilt modes.

Based on the derived requirements, we use a piezo piston,tip-tilt actuator *S-325.3SL* from the company *Physik Instrumente* (PI), because the actuator covers the travel range and can be used for high frequency oscillations. The actuator consists of three piezo stacks, which move a plate in three degree of freedom. The piezo stacks are connected with the plate by flexible joints. Each stack has an internal position control. We use a classical PI controller and a notch filter to prevent the excitation of the resonance frequency. However, we have to consider, that the actuator is designed for mounting low weights, especially optical mirrors. As mentioned above, we want to measure the mirror motion with accelerometers, which are fixed on a specific point away from the pivot point because of the required accelerations. The sensors are fixed on a metal plate and mounted on the mirror. Adding such a mass reduces the resonance frequency tremendously. Here we have to ensure that the resonance frequency is larger than the 20 Hz and the forces at the actuators are in the specified range. For minimizing the weight we decide to use resistive MEM accelerometer from *Silicon Design*, but we had to ensure that the resolution is sufficient. We calculate the resolution by assuming a harmonic oscillation $\ddot{x} = -\omega_0^2 x$ of the tip-tilt modes and a minimum amplitude of 2 μrad at 8 Hz. We get a minimum accuracy of 250 μm/s^2 5 cm away of the pivot point. The accelerometers have a measurement accuracy of 240 μm/s^2. The designed disturbance mirror is depicted in Fig. 3. 4 accelerometers are screwed to the plate. Number and position of the sensors is discussed in the next section. We choose a plate thickness of 2 mm to ensure that the resonance frequency is far away from the disturbance frequencies. The mechanical behaviour of the system was analysed by exciting the system with 17 Hz and 21 μrad to get a good signal quality for the input signal. The results are shown in Fig. 4. The resonance frequency is at around 230 Hz. Furthermore, there are peaks at 50 Hz and higher harmonics, because of electromagnetic disturbances. From 0 Hz to 5 Hz is a broadband disturbance. This disturbance is difficult to eliminate by a high pass filter, because of the considerable phase change.

3. TIP-TILT RECONSTRUCTION

For reconstructing the tip-tilt modes from the accelerometer data, the kinematics of the disturbance mirror have to be known. The plate is a rigid body with three degree of freedom. It can be displaced along the z-axis and rotated around the x- and y-axis depicted in Fig. 3. The mirror