Disturbance Feedforward Control for Vibration Suppression in Adaptive Optics of Large Telescopes

Martin Glück, Jörg-Uwe Pott, Oliver Sawodny
Disturbances affecting the Telescope Resolution

- Atmospheric Turbulences
- Structural Vibrations

Adaptive Optics

Observations with Faint Guide Stars

- Long exposure for better Signal-to-Noise-Ratio
- Adaptive Optics (AO) loop speed is reduced
- High frequency Vibrations are seen at the Telescope Mirror (> 5 Hz)
- Classical AO loop is to slow

Accelerometer-based Disturbance Feedforward
Compensation of the Telescope Vibrations

- Measuring vibrations at relevant telescope mirrors with additional accelerometers
- Reconstruction of the Optical Modes influenced by Vibrations (Piston, Tip, Tilt Zernike Modes)
- Compensating by the Tip-Tilt mirror and Deformable Mirror
  - Independent of the Wavefront Exposure Time
  - Suppression of high frequency Vibrations
1. Methods for Vibration Suppression

2. Simulation Results

3. Conclusion and Outlook
Overview Adaptive Optics

1. Classical Integration

2. Observer-based Disturbance Suppression

\[ \phi_{\text{res},d} = 0 \]

Controller (R)

Deformable Mirror (DM)

Wavefront Sensor (WFS)

Vibrations (vib)

Atmospheric Turbulences (turb)

\[ \phi_{\text{vib}} \]

\[ \phi_{\text{turb}} \]

\[ \phi_{\text{cor}} \]

\[ \phi_{\text{res}} \]
Assumptions

- DM $\approx 1$ (fast position control)
- 2 sample delay of the WFS

Disturbance Modelling

- Atmosphere
  - Approximation of the temporal power spectral density by a second order AR model
    \[ X_t = a_1 X_{t-1} + a_2 X_{t-2} + \epsilon_t \]

- Vibrations
  - Modal representation of the mechanical system (considering dominant natural frequencies)
    \[ \ddot{x} + 2d\omega_0 \dot{x} + \omega_0^2 x = u \]
**Concept**

- Measuring Vibrations with Accelerometers at Telescope structure

- Reconstructing Optical Modes (Piston, Tip, Tilt, Defocus)
  - Different Tip-Tilt Sensitivity of each Mirror

- Adding to the Control Input of the Adaptive Mirrors (M4, M5)
  - Considering time delay
Reconstruction Algorithms for the Optical Modes

Challenges

- Online Double Integration of Accelerometer Signals
  - Unstable
  - Time Delay

Reconstruction Methods

- Approximation of a Double Integrator by a Bandpass Filter, Böhm[2]
- Disturbance Observer
  - Modal Model of the Mechanics
  - Luenberger Observer Design
- Adaptive Resonator, Keck[1]
  - Using Online Fourier Analysis

\[ \ddot{\varphi}_{AR,i} = A \cos(\omega_1 t) + B \sin(\omega_1 t) \]
\[ \varphi_{AR,i} = -\frac{1}{\omega_1^2} \dot{\varphi}_{AR,i} \]

\[
\begin{pmatrix}
0 \\
\omega_0^2
\end{pmatrix} x +
\begin{pmatrix}
0 \\
1
\end{pmatrix} u
y = [ -\omega_0^2 \ 0 ] x
\]

\[
\hat{x} = A \hat{x} + L (y - \hat{y}), \quad \hat{y} = C \hat{x}
\]

\[
A = \int_0^t g(\dddot{z}_i - \dddot{z}_{AR,i}) \cos(\omega_1 \tau) \, d\tau
\]

\[
B = \int_0^t g(\dddot{z}_i - \dddot{z}_{AR,i}) \sin(\omega_1 \tau) \, d\tau
\]
Comparison of the Reconstruction Methods

![Amplitude vs Frequency Graph]

- AR
- KF
- BP
- I

![Phase vs Frequency Graph]

- AR
- KF
- BP
- I
Schematic View of an Adaptive Optics with an additional DFF

\[
\phi_{res,d} = 0
\]

- Controller (R)
  - u_{FB}
  - u_{FF}
  - u

- Wavefront Sensor (WFS)

- Accurators (ACC)
  - Reconstruction Filter (RF)

- Vibrations (vib)
  - \(\phi_{vib}\)

- Atmospheric Turbulences (turb)
  - \(\phi_{turb}\)

- Deformable Mirror (DM)
  - \(\phi_{cor}\)

- DFF

- \(\phi_{res}\)
Comparison of the Disturbance Compensation Methods

Simulation Parameters
- Wind velocity 10 m/s
- Natural frequencies at 10 Hz and 13Hz
- Sample Rate Accelerometers 1 kHz
- Disturbance Feedforward Control with a Kalman Reconstructor

Error - Transfer Function

\[ G_d(s) = \frac{\varphi_{res}}{\varphi_{vib}} \]

Graph showing the Exposure Time 1 ms and Exposure Time 10 ms with different lines representing Integral Control, Observer-based Disturbance Compensation, and Disturbance Feedforward.
1. Methods for Vibration Suppression

2. Simulation Results

3. Conclusion and Outlook
Simulation Results for a bright Guide Star

Integral Control

Observer-based Disturbance Compensation

Disturbance Feedforward

Bright guide star 10 mag und exposure time 800 Hz

Typical atmospheric condition 0.8 arcsec

Exciting the system by varying the natural frequency 0 Hz ... 50 Hz
Simulation Results for a faint Guide Star

- Faint guide star with 14.6 mag and exposure rate 200 Hz
- Exciting the system by varying the natural frequency 0 Hz ... 50 Hz
1. Methods for Vibration Suppression
2. Simulation Results
3. Conclusion and Outlook
Conclusion

- High frequency vibrations worsen the performance for observations with faint guide stars
- Improving the performance with an Accelerometer-based Disturbance Feedforward control

Outlook

- Considering the influence of the actuator dynamics (M4, M5)
- Testing Disturbance Feedforward at the LBT
Thank You! Questions?

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