CHEOPS – CHaracterizing Exoplanets by Opto-infrared Polarimetry and Spectroscopy

CHEOPS Group

CHEOPS Deformable Mirrors - A note on Piezo Actuator Dynamical Properties –

Doc. No. CHEOPS-SPE-MPI-00070

Issue 2.0

October 13, 2004

	Name	Date	Signature
Prepared	Stefan Hippler	October 13, 2004	
Approved	Markus Feldt	October 13, 2004	
Released	Wolfgang Brandner	Oct. 18, 2004	

This page was intentionally left almost blank

Change Record

Issue/Rev.	Date	Section/Parag. affected	Reason/Initiation/Documents/Remarks
1.0	July 26, 2004	all	first draft
2.0	October 13, 2004	all	final issue

Contents

Acronyms

AD	Applicable Document
AO	Adaptive Optics
CHEOPS	CHaracterizing Extra-solar planets by Opto-infrared Polarimetry and Spectroscopy
DM	Deformable Mirror
MPIA	Max-Planck-Institut für Astronomie
PMN	Lead-Magnesium-Niobium ceramics
PZT	Lead-Zirconium-Titanate Piezo ceramics
RD	Reference Document
RTC	Real-Time Computer

1 Applicable documents

AD1 CHEOPS Deformable Mirrors — Xinetics DM Availability, CHEOPS-SPE-MPI-00008.

AD2 CHEOPS DM Characterization Report, CHEOPS-TRE-SWL-00053.

2 Reference documents

RD1 Physik Instrumente Piezo Tutorial.

3 Introduction

3.1 Scope

This document gives an overview about some of the dynamical properties of piezo actuators. These properties determine the minimum response time of the actuator, and correspondingly the maximum frequency at which the actuator can operate efficiently.

4 How fast can a Piezo actuator expand?[1]

4.1 Resonant frequency

In general, the resonant frequency of any spring/mass system is a function of its stiffness and effective mass (see Fig. 1). The resonant frequency given in the technical data tables always refers to the unloaded actuators, with one end rigidly attached. The resonant frequency of an ideal spring/mass system is gives as:

$$f_0 = \left(\frac{1}{2\pi}\right)\sqrt{\frac{k_T}{m_{eff}}} \tag{1}$$

[1]This is taken mainly from [RD1]

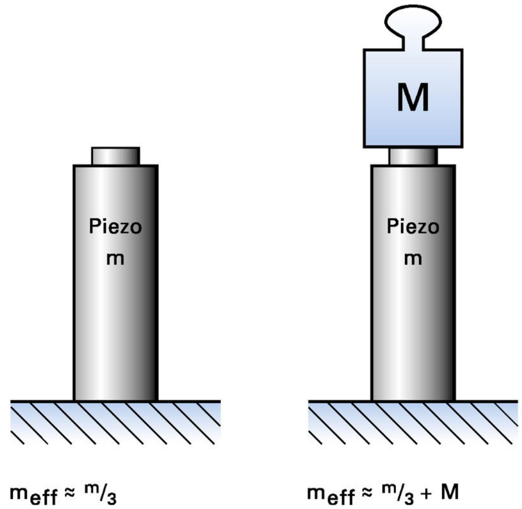

Figure 1: Effective mass of an actuator fixed at one end.

where:

f_0 = resonant frequency [Hz]

k_T = actuator stiffness [N/m]

m_{eff} = effective mass [kg] (about 1/3 of the mass of the ceramic stack plus any installed end pieces)

Note: Due to the non-ideal spring behavior of PZT ceramics, the theoretical result from the above equation does not necessarily match the real-world behavior of the PZT system under large signal conditions. An additional complication is that the stiffness of the DM surface adds a second spring to the system. The influence of the DM surface is considered to be of secondary importance, as the forces associated with the DM surface are smaller, seen in the inter-actuator coupling in [AD1] and [AD2].

When adding a mass M to the actuator, the resonant frequency drops according to the following equation:

$$f_0^r = f_0 \sqrt{\frac{m_{eff}}{m_{eff}^r}} \tag{2}$$

Eqn. 2: Resonant frequency with new effective mass m_{eff}^r = additional mass M + m_{eff}.

The above equations show that increasing the effective mass of the loaded actuator by a factor of 4 will reduce the response (resonant frequency) by a factor of 2. Increasing the spring preload on the actuator does not significantly affect its resonant frequency.

The phase response of a PZT system can be approximated by a second order system and is described by the equation:

$$\phi \approx 2 \cdot \arctan \frac{f}{f_0} \tag{3}$$

ϕ = phase angle [deg]

f_0 = resonant frequency [Hz]

f = operating frequency [Hz]

Fast response is one of the desirable features of piezo actuators. A rapid drive voltage change results in a rapid position change. This property is necessary in applications such as switching of valves/shutters, generation of shock-waves, **vibration cancellation** systems, etc.

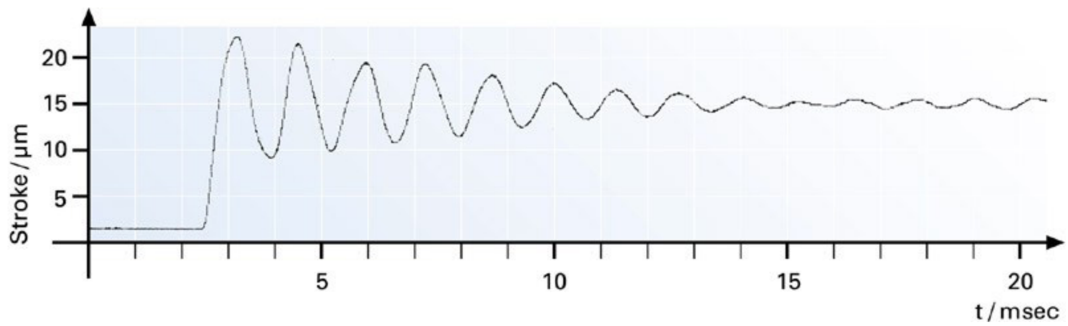

Figure 2: Response of an undamped, lever-amplified PZT actuator (low resonant frequency) to a rapid drive-voltage change.

A PZT can reach its nominal displacement in approximately 1/3 of the period of the resonant frequency, albeit with significant overshoot (see Fig. 2).

$$T_{min} \approx \frac{1}{3 f_0} \tag{4}$$

Eqn. 4: Minimum rise time of a piezo actuator (requires an amplifier with sufficient output current and rise time).

For example, a piezo translator with a 10 kHz resonant frequency can reach its nominal displacement within 30 μs.

5 Electrical requirements for Piezo operation[2]

When operated well below the resonant frequency, a PZT behaves as a capacitor: displacement is proportional to charge (first order estimate).

PZT stack actuators are assembled with thin, laminar wafers of electroactive ceramic material electrically connected in parallel. The (small-signal) capacitance of a stack actuator can be estimated by:

[2]This is taken mainly from [RD1]

$$C \approx n \cdot \varepsilon_{33T} \cdot \frac{A}{d_s} \tag{5}$$

Where:

$n = \frac{l_0}{d_s}$ = number of layers

ε_{33T} = dielectric constant [As/Vm]

A = electrode surface area of a single layer [m^2]

d_s = distance between the individual electrodes (layer-thickness) [m]

l_0 = actuator length

The equation explains that for a given actuator length $l_0 = n \cdot d_S$ and a given disk thickness d_S, the capacitance is a quadratic function of the ratio d_S/d_1 where $d_1 < d_S$. Therefore, the capacitance of a piezo actuator constructed of 100 μm thick layers is 100 times the capacitance of an actuator with 1 mm thick layers if the two actuators are the same length.

Static Operation

When electrically charged, the energy $E = (1/2)CU^2$ is stored in a piezo actuator. Every change in the charge (and therefore in the displacement) of the PZT requires a current I:

$$I = \frac{dQ}{dt} = C\frac{dU}{dt} \tag{6}$$

Eqn. 6: Relationship of current and voltage for the piezo actuator.

Where:

I = current [A]

Q = charge [coulomb (As)]

C = capacitance [F]

U = voltage [V]

t = time [s]

Dynamic Operation (Switched)

For applications such as shock wave generation or valve control, switched operation (on / off) may be sufficient. PZTs can provide motion with rapid rise and fall times with accelerations up to thousands of g's. Equation 7 relates applied voltage (which corresponds to displacement) to time.

$$U(t) = U_{bias} + U_{comm} \cdot \left(1 - e^{-t/RC}\right) \tag{7}$$

Eqn. 7 Voltage on the piezo after applying the desired voltage U_{comm}.

Where:

U_{bias} = bias voltage [V]

U_{comm} = commanded drive voltage [V]

R = resistance in drive circuit [V]

C = PZT actuator capacitance [F]

The voltage rises or falls exponentially with the *RC* time constant. Under static conditions the expansion of the PZT is proportional to the voltage. In reality, dynamic PZT processes cannot be described by a simple equation. Whenever the PZT expands or contracts, dynamic forces act on the ceramic material. These forces generate a (positive or negative) voltage in the piezo element which adds to the drive voltage. *A PZT can reach its nominal displacement in approximately one third of the period of the resonant frequency* (see section 4). For example, a piezo element with 10 kHz resonant frequency can reach its nominal displacement within 30 μs if amplifier current and rise time are sufficient.

If the voltage rises fast enough to excite a resonant oscillation in the PZT, ringing and overshoot will occur. For charging with constant current (e.g. that provided by a linear amplifier), the following equation applies:

$$t \approx C \cdot (U_{comm}/I_{max}) \tag{8}$$

Eqn. 8: Time to charge a PZT with constant current. (Minimum amplifier rise time must also be considered).

Where:

t = time to charge to U_{comm} [s]

C = PZT actuator capacitance [F]

U_{comm} = commanded drive voltage [V]

I_{max} = peak amplifier source/sink current [A]

For fastest settling, switched operation is not the best solution. If the input signal rise time is limited to $1/f_0$ the overshoot can be reduced significantly. Preshaped input signals (optimized for minimum resonance excitation) reduce the time to reach a stable position.

6 Characteristics of the MPIA Xinetics 97 and 349 Actuators Deformable Mirrors

We have measured the static capacitance and the effective electrical resistance of an actuator as well as the dynamical voltage behaviour. The capacitance measured was C=1μF and the effective resistance was R=200Ω. From Figure 3 we find a maximum stroke of 6.8 μm at a voltage of 70 V. The calculated time constant RC is 200 μs. This leads to a theoretical rise time of 2.3 RC=460 μs to reach 90% of the commanded voltage. From Figure 4 we find a voltage change per time interval of:

$$dU/dt = 4V/600\mu s \propto 389nm/600\mu s \approx 650nm/ms \tag{9}$$

This is the speed of an actuator in nanometers per milli-second.

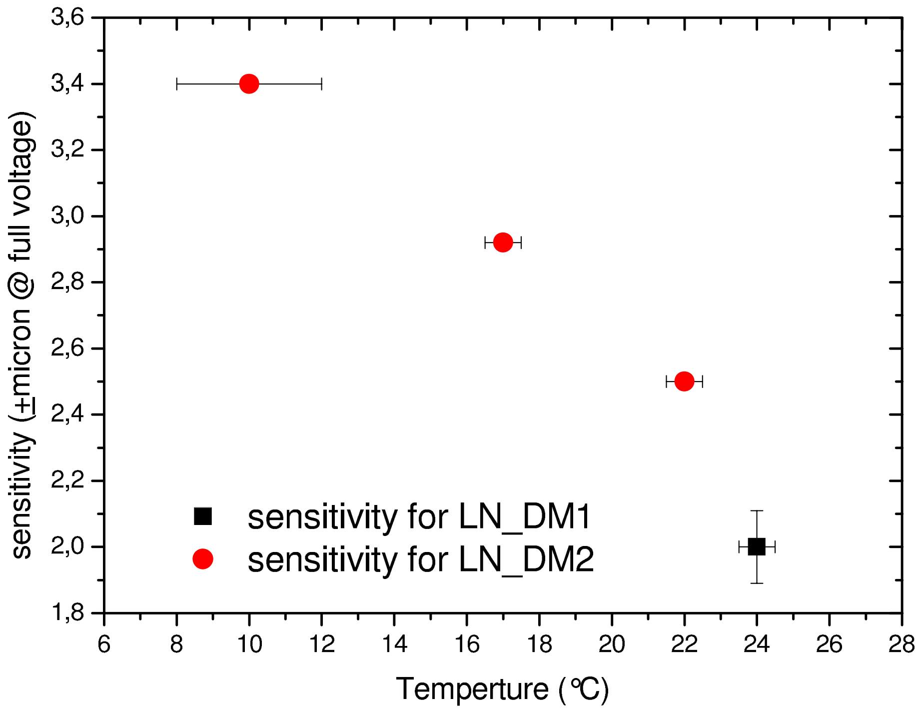

Figure 3: Maximum stroke of a 349-actuator DM as a function of operating temperature.

7 What is the maximum acceptable time between sending a command from the RTC to the actual physical motion of an actuator or all actuators on the mirror?

As outlined in the previous sections a single piezo ceramic actuator can reach its nominal displacement in about one third of its resonance period. Typical resonance frequencies of piezo stack actuators are in the $>$ 10kHz regime. Please note that the resonance frequency of the entire mirror can be different from this value. Reported values for piezo stack deformable mirrors range from a few kHz to a few 10 kHz depending on the design of the deformable mirror.

For CHEOPS with its required high sampling frequency of 2 kHz (5 kHz goal), latencies with respect to DM control shall be below one fifth of the sampling time, ie below 100 μs and 40 μs (goal) resp. The electrical latency time in this context is given as the time difference from sending the command from the RTC to the DM control electronics to when the amplifier outputs 90% of the commanded voltage. This means that the mirror has actually moved (a bit, depending on its mechanical resonance frequency).

This latency requirement is therefore a combined requirement for the RTC, the DM control electronics, and the DM.

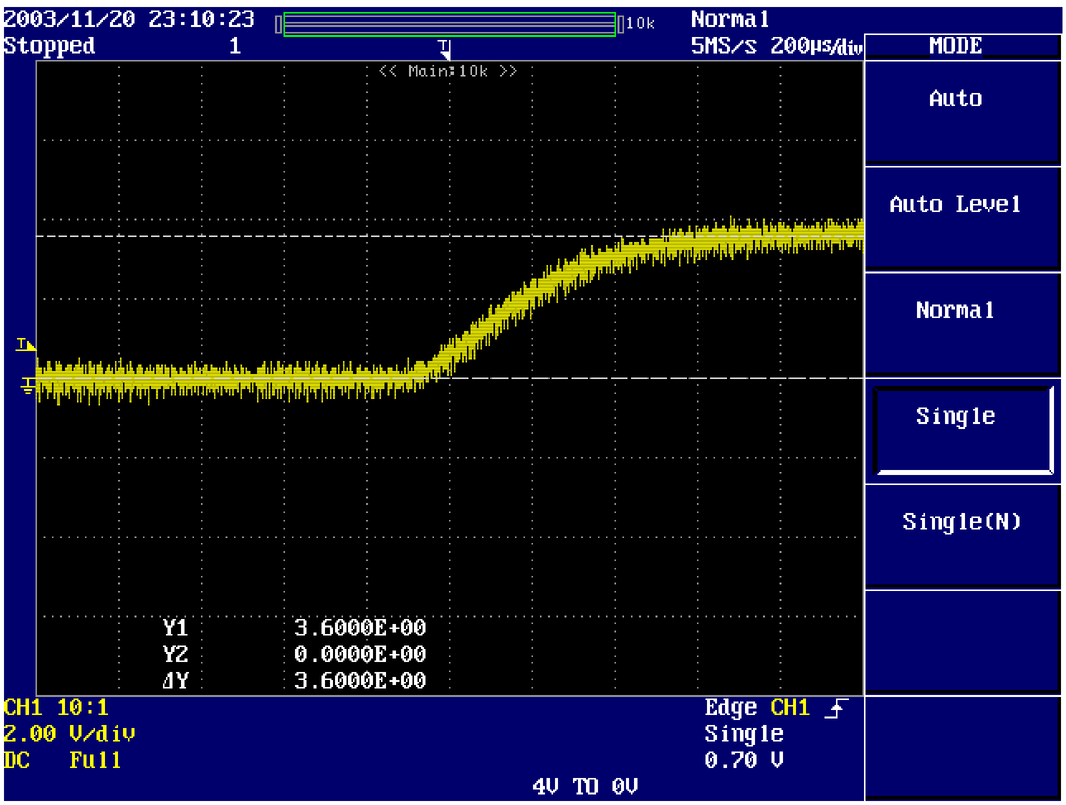

Figure 4: Voltage as a function of time for a piezo-stack actuator of the 97-actuators DM. Scale on y-axis is 200 μs per division and on the x-axis 2 V per division.