Performance of a magnetic driven Tip–Tilt mirror

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ABSTRACT

ThermoTrex Corporation has designed and built a prototype of the Fast Steering Mirror to be used for image motion control in the TNG Adaptive Optics System. The principal characteristic of this mirror is the use of voice coil actuators whose positions are controlled with closed loops based on capacitive sensors. Here we report the main features of the mirror assembly and laboratory measurements done to characterize the mirror behavior. The Bode diagram of the mirror is reported and discussed.

1. INTRODUCTION

The Tip–Tilt Mirror (TTM hereafter) is a crucial component of any Adaptive Optics system. Usually, piezoceramic–actuated mirror platforms have been used. In this paper we briefly show the experimental results on a prototype of a TTM produced by ThermoTrex Corporation. The mirror has been delivered in the framework of the Adaptive Optics for the TNG telescope\(^1\). While joint tests between industry and research institute on this TTM have been performed in the early stages of manufacturing of the TTM, the test described in this paper has been performed in a research institute and are here shown with comparison with other existing TTM.
2. THE TIP-TILT MIRROR DESIGN

The tip-tilt mirror described in this paper is a prototype unit built by ThermoTrex Corporation for use in astronomical adaptive optics systems. The flat mirror is 100 mm diameter, with a beam deflection up to 1 milliradian. Tilt command to the mirror can be sent either as analog signals or as digital words; all of the interior electronics uses analog signals. The mechanical design uses a flexure pivot, eliminating backlash. The mirror position is actuated by opposing voice coil pairs, using capacitance position sensors to assure linearity.

The tip-tilt mirror system is composed of an optical head and an electronics unit. Cables five meters long separate the units. The 100 mm diameter mirror uses a fused silica substrate 19 mm thick. An actuated reaction mass attached to the same mount provides momentum cancellation. The mirror tilt is measured with capacitance position sensors directly attached to the back of the mirror, which send analog outputs to the electronics unit. The optical head contains all of the capacitance sensor electronics and reference signals.

The electronics unit contains the analog control loop, a type of proportional-integral-differential (PID) control loop. The capacitance sensors are used in a differential mode to drive the PID circuit, so true tilt is accurately measured. The electronics unit also contains the voice coil current drivers, the interface electronics, and the DC power supplies.

3. TTM CHARACTERIZATION

At the Arcetri optical laboratory the TTM has been placed in a simple setup configuration, illuminating it with an HeNe laser beam in a nearly autocollimating configuration. After refocusing, the resulting spot illuminates a four-quadrant sensor. The noise within the sensor itself has been proven to be negligible with respect to all of the other measurements described in this paper. Moreover, the TTM can be rotated in order to align the detector's axis with the tilt mirror. The mirror has been driven by a programmable synthesiser while the sensor's data has been collected by a commercial VME board used up to a \( \approx 500 \text{kHz} \) rate. As a double check, a digital dual-trace oscilloscope has been used to verify the phase measurements. This set-up avoids the well known problems encountered at the very low frequencies when using most commercial spectrum analysers.

The Bode diagram, both in phase and amplitude, for the two axes of the TTM, has been obtained. The two diagrams look very similar to each other and in the following we refer to the X axes only. A preliminary and qualitative analysis of the results can be useful to understand the TTM performance and to drive the following investigations. From the amplitude Bode diagram (see Fig.1a) one can see a steep decreasing occurring from \( f \approx 300 \text{Hz} \). From control system theory it is well known that this behaviour is described by a pair of conjugate poles in the frequency domain. Moreover we know in advance that the electronics inside the TTM provides additional filtering at a given frequency, the exact value depending upon the adjustment of the analog electronics. Hence, we expect that the Bode diagrams should be well fit by a three pole transfer function.

Other experimental facts that lead to the estimation of the number of poles are the asymptotic behavior of the phase Bode diagram (see Fig.1b) to roughly \( 270^\circ \) (also typically of third-order systems) and the slope at the high frequency side of the amplitude diagram at \( \approx 40 \text{db/decade} \) (recall that a simpler, two pole system will exhibit a 20db/decade slope).

The transfer function \( TF(\omega) \) is defined as the ratio between the output and the input of a given system. The Fourier transform (FT hereafter) of the input is a function of the frequency \( \hat{I}(\omega) \) (being the frequency \( \omega \) expressed in rad/sec, where \( \omega = 2\pi f \) links Hz with rad.s\(^{-1} \)) and may be expressed in the complex notation as:

\[
\hat{I}(\omega) = I e^{i\alpha}
\]  

where \( I = I(\omega) \) is the module and \( \alpha = \alpha(\omega) \) is the argument of \( \hat{I}(\omega) \). The FT of the output \( \hat{O}(\omega) \) is again a
Figure 1: a): Amplitude (top) and b): phase Bode diagram (bottom).
function of the frequency, normally with a different modulus and with a phase displacement $\phi(\omega)$ with respect to the input:

$$\tilde{O}(\omega) = O(\omega)e^{i(\alpha + \phi(\omega))}$$

(2)

Let us now write the transfer function $TF$ itself as:

$$TF(\omega) = \frac{O(\omega)e^{i(\alpha + \phi(\omega))}}{I(\omega)e^{i\alpha}} = \frac{O(\omega)}{I(\omega)}e^{i\phi(\omega)} = M(\omega)e^{i\phi(\omega)}$$

(3)

where $M(\omega)$ is the amplitude of the transfer function, and $\phi(\omega)$ is the argument of the transfer function, both known from the test of the TTM.

Using now Euler's formulas, we have:

$$TF(\omega) = M(\omega)\cos(\omega) + M(\omega)i\sin(\omega) = A + iB$$

(4)

where we have dropped the dependence from $\omega$ in both $A$ and $B$ for the sake of simplicity.

We obtain:

$$A + iB = \frac{(A + iB)(A - iB)}{A - iB} = \frac{A^2 + B^2}{A - iB} = \frac{1}{\frac{A}{A^2 + B^2} - i\frac{B}{A^2 + B^2}} = \frac{1}{\hat{A} - i\hat{B}}$$

(5)

where $\hat{A} = \frac{A}{A^2 + B^2}$ and $\hat{B} = \frac{B}{A^2 + B^2}$.

Assuming the 3-pole $TF$ defined by the 4 coefficients $a$, $b$, $c$ and $d$ is given by the following:

$$TF(\omega) \approx \frac{1}{a(\omega)3 + b(\omega)2 + c\omega + d} = \frac{1}{(d - b\omega^2) - i(a\omega^3 - c\omega)}$$

(6)

we can easily obtain the pair of relationships:

$$\begin{cases}
\hat{A}(\omega) = d - b\omega^2 \\
\hat{B}(\omega) = a\omega^3 - c\omega
\end{cases}$$

(7)

A standard fit to the experimental results gives the following set of parameters:

$$\begin{cases}
a = 2.52 \times 10^{-10}s^3 \\
b = 5.37 \times 10^{-7}s^2 \\
c = 1.26 \times 10^{-3}s \\
d = 1.01
\end{cases}$$

(8)

While this approach characterizes the tip-tilt unit in a very complete manner (although with still a small amount of uncertainty), a more concise approach characterizing the tip-tilt performance is described here. First
Figure 2: Phase Bode diagram with a linear fit shows a fixed delay $\tau$ for the experimental results of the TTM described in the text and for some other TTMs for which data are available in the literature.

...of all, the amplitude diagram is not taken into consideration, and the phase Bode diagram is fitted with a linear relationship. This translates into the assumption that the mirror has a fixed delay-time. In Fig.1 one can see the best fit obtained for the mirror under consideration in this paper, together with some other tip–tilt mirror units of comparable size$^{2,3,4}$ (for the tip–tilt mirror used in ADONIS we have taken into consideration the delay–time of the worst axes, being the latter the one that dominates the degradation of the PSF as recovered by the scientific instrument). A $\tau \approx 1.35\text{ms}$ is obtained for the mirror under consideration here. As it can be easily seen, the departure from the fit is not negligible; however, we prefer to not speculate on the possibility to derive better (i.e. lower $\tau$) performance, limiting the range of interest to a given frequency interval.

4. SCALING CONSIDERATIONS

The final TTM to be incorporated onto the AdOpt@TNG module will be slightly modified with respect to the TTM considered here. While it is clear that only a second series of tests can provide the performance of the new TTM, some scaling considerations can be used to predict the expected performance with some degree of precision.

We consider the force $F$ applied from the actuators to the mirror (Fig.3), and using the definition of momentum $\vec{M}$ of a force with respect to the center of the mirror one can write:

$$\vec{M} = \vec{R} \times \vec{F} = RF \sin(\phi)\vec{k}$$ (9)
where $\vec{k}$ is a vector normal to the plane of the figure and entering it.

Applying the dynamic laws of rotational motion, where $\vec{L}$ is the angular momentum of the mirror (it can be written as $\vec{L} = I \vec{\omega}$ where $I$ is the moment of inertia and $\vec{\omega}$ is the angular velocity of the mirror, equivalent to $\vec{\omega} = \phi \vec{k}$), we can write the momentum as:

$$\dot{M} = \frac{d\vec{L}}{dt} = I \frac{d\vec{\omega}}{dt} = I \phi \vec{k}$$ \hspace{1cm} (10)

Using the approximation $\sin(\phi) \approx \phi$, we can easily obtain the differential equation:

$$I \phi = RF \phi$$ \hspace{1cm} (11)

whose solution is:

$$\phi(t) = A \cos(\omega t + \phi) \quad \text{with} \quad \omega = \sqrt{\frac{FR}{I}}$$ \hspace{1cm} (12)

Since $I \propto mR^2$, where $m$ is the mass of the mirror and $m \propto tR^2$, where $t$ is the thickness of the mirror, we can find that the attainable frequency is proportional to:

$$\omega \propto \sqrt{\frac{F}{R^3 t}}$$ \hspace{1cm} (13)

We have now the possibility to estimate how the frequency changes with a new thickness of 18 mm (instead of 19 mm of the tested mirror) and with a new diameter of 90 mm (instead of 100 mm) and with a more powerful force exerted by larger coils, a factor \( \approx 2 \) stronger:

$$\frac{\omega_{\text{new}}}{\omega_{\text{old}}} \approx \left( \frac{90}{100} \right)^{-\frac{1}{2}} \left( \frac{18}{19} \right)^{-\frac{1}{2}} (2)^{\frac{1}{2}} \approx 1.7$$ \hspace{1cm} (14)

If confirmed, this should lead to a delay–time of the order of $\tau \approx 0.8$ mSec. Other cases can be easily turned out using the scaling relationship obtained.
5. CONCLUSIONS

The performance of the TTM tested here appears to lie in the border edge of the TTM with \( \approx 100\text{mm size} \) and the scaling consideration for the final device looks even more interesting. The new TTM will be extensively tested in the laboratory in order to fully characterize the final tip–tilt loop. The more interesting test, the one in the sky with astronomical targets, is expected to take place on the Canary Islands in the first months of next year.

6. REFERENCES


