Designing the Actuator for the Next-Generation Astronomical Deformable Mirrors: a Multidisciplinary and Multiphysics Approach

Comsol for Adaptive Optics

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1. Background
   - The AO Principle
   - The Design Drivers
2. The Actuator
   - The Multiphysics Problem
   - The Model
3. The Application Modes
   - Magnetostatics
   - Heat transfer
   - Fluid dynamics
4. Results
5. Experimental Validation
Compensating the Atmospheric Turbulence
The Control System Concept
Adaptive Optics on board the Telescope

System Overview

Riccardi et al., 2004
Actuating the DM & Sensing the Displacements
The LBT Voice-Coil
Outline

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5. Experimental Validation
Basic Requirements of High Order DM’s
The Specs are very Severe

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>rms force (turb. corr.) [N]</td>
<td>0.363</td>
</tr>
<tr>
<td>max force (static) [N]</td>
<td>0.36</td>
</tr>
<tr>
<td>max force (dynamic) [N]</td>
<td>1.27</td>
</tr>
<tr>
<td>stroke [μm]</td>
<td>±150</td>
</tr>
<tr>
<td>bandwidth [kHz]</td>
<td>1</td>
</tr>
<tr>
<td>typical actuator spacing [mm]</td>
<td>25</td>
</tr>
<tr>
<td>typical mover mass [g]</td>
<td>≤ 10</td>
</tr>
<tr>
<td>resistance [Ω]</td>
<td>2 to 2.5</td>
</tr>
<tr>
<td>measuring range [μm]</td>
<td>±100</td>
</tr>
<tr>
<td>resolution [nm]</td>
<td>&lt; 3</td>
</tr>
<tr>
<td>rms noise [nm]</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>drift(^1) [nm]</td>
<td>20</td>
</tr>
<tr>
<td>bandwidth [kHz]</td>
<td>&gt; 30</td>
</tr>
</tbody>
</table>

\(^1\) 12 hrs base, 5°C temperature variation
DM Stiffness vs. DM Thickness & Act Spacing

\[ K_{\text{flex}} \propto t^3 \times (1/d)^4 \]

- What if
  - the inter-actuator spacing is slightly reduced
  - the thickness is slightly increased

\[
\begin{align*}
\text{HIGHER ORDER DM} & \quad d = 30 \rightarrow 25 \text{ mm} \ (16\%) \\
\text{ELT PANELS} & \quad t = 1.6 \rightarrow 2 \text{ mm} \ (20\%) \\
\end{align*}
\]

\[ \sim 2 \times K_{\text{flex}} \]
The Design Criterion: Avoid Thermal Pollution
The Basic Question & Two Possible Answers

reduce the *local seeing*

↓

reduce any local heating

↓

given the force, reduce the power

↓

maximize the efficiency, i.e. the force-to-power ratio
(while respecting the geometry and minimizing the emc)

How getting $\Delta T \leq \pm 1 \text{ K}$ on any air-exposed surface?

1. implement a cooling system
   - *active* (which $T_{\text{co}l\text{a}nt}$?)

2. rely on the natural convection
   - *passive*

SAFER BUT MORE COMPLEX

SIMPLER BUT MORE RISKY
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The Electromagnetic Core
Variable Reluctance LM: Magnetic Force = \( \int_V (\mathbf{M} \cdot \nabla) \mathbf{B} \, dV \)

[Del Vecchio et al., 2008]
The Electromagnetic Core

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The Axially Symmetric Actuator
E/M and E/S Components

motor (statoric)
capsens (statoric)
motor (moving) & shaft
capsens (moving)
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E/M and E/S Components

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Novel AO Act
Del Vecchio, Biasi, Riccardi, Gallieni

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motor (statoric)
capsens (statoric)
motor (moving) & shaft
capsens (moving)
The Axially Symmetric Actuator

The Other Components

static
motor capsens

moving
motor shaft capsens
membranes
top/bottom plates
body (& aux)
From the Dwg to the Mesh
Carefully Meshing Gap & Coil Regions

- 2d geometry imported via the CAD Import Module
- Fine mesh of coil \( r_{wire} = 0.1195 \text{ mm}, \delta_{ins} = 7 \mu\text{m} \) and air gaps \( \tau = 7 \mu\text{m} \)
- As a result
  - \( \approx 55,000 \) points and \( \approx 100,000 \) elements
  - 0.5% of which have a quality \( \leq 0.4 \)
  - minimum quality = 0.19
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Setting Up the Magnetostatics

Temperature Affects the Resistive Heating

\[ F = \int_S -\frac{1}{2} (\mathbf{H} \cdot \mathbf{B}) \mathbf{n} + (\mathbf{n} \cdot \mathbf{H}) \mathbf{B}^T \, dS = \int_V (\mathbf{M} \cdot \nabla) \mathbf{B} \, dV \]

choose the Maxwell tensor

\[ \sigma_{Cu} = \frac{1}{\rho_{Cu_{ref}}} \left[ 1 + 0.0039 (T - 293) \right] \quad \text{S} \times \text{m}^{-1} \]

\[ \rho_{Cu_{ref}} = 1.72 \times 10^{-8} \, \Omega \times \text{m} \quad \text{Cu resistivity @ 293 K} \]

\[ T \leftarrow \text{heat transfer} \]
Setting Up the Heat Transfer
Assumption & Restrictions

- neglect the radiative contribution
- $\frac{\partial k}{\partial T} \approx 0$ in conductive solids
- trapped air isn’t convective
- convective air
  - $\rho = \frac{M}{R} \frac{p + p_{atm}}{T} = 3.484 \times 10^{-3} \frac{p}{T}$ [Pa] \( \leftarrow pV = nRT 
    - $p \leftarrow$ weakly compressible Navier-Stokes
    - $p_{atm} = 101325$ Pa
  - $u_{air} \leftarrow$ weakly compressible Navier-Stokes
- boundary conditions
  - $T = T_{ref}$ @ bottom
  - thermal insulation @ vertical outer bnd
  - convective flux @ top
  - $T = T_{coolant}$ @ coolant channels bnd’s (if any)
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Setting Up the Weakly Compressible N-S Assumption & Restrictions

\[ \rho = \frac{M p + p_{atm}}{T} = 3.484 \times 10^{-3} \frac{p}{T} \quad [\text{kg} \times \text{m}^{-3}] \quad \leftrightarrow \quad pV = nRT \]

\[ \eta = -7.887 \times 10^{-12} T^2 + 4.427 \times 10^{-8} T + 5.204 \times 10^{-6} \quad [\text{Pa} \times \text{s}^{-1}] \]

\[ f_z = 9.81 (\rho_{ref} - \rho_{chns}) \quad [\text{N}] \]

\[ \rho_{ref} = \rho @ (T = T_{ref}, p = 0) \]

boundary conditions

\[ u = 0 \quad \text{(wall / no slip)} \quad @ \text{air-solid interfaces} \]
\[ n \cdot u = 0 \ldots \quad \text{(wall / slip)} \quad @ \text{vertical outer bnd} \]
\[ p = 0 \ldots \quad \text{(outlet / normal stress)} \quad @ \text{horizontal top bnd} \]
Magnetostatic Results I
\[ \epsilon > 4 N \times W^{-1} \]

- \[ .57 \leq \Delta T_{Cu} \leq 3.98 \text{ K}, \text{ thanks to material optimization} \]
- \[ 4.05 \leq \epsilon \leq 4.1 N \times W^{-1}, \text{ thanks to geom. optimization} \]

1. rms turb. corr. force \[ .363 \text{ N} \rightarrow .21 \text{ A} \]
2. max dyn. force \[ 1.27 \text{ N} \rightarrow .38 \text{ A} \]

### A low-order actuator vs. the current high order actuator

<table>
<thead>
<tr>
<th>Force</th>
<th>LBT</th>
<th>TEC1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \int_V (J \times B) , dV )</td>
<td>( \int_V (M \cdot \nabla) B , dV )</td>
<td></td>
</tr>
<tr>
<td>power @ 1.27 N [W]</td>
<td>4.169</td>
<td>.314</td>
</tr>
<tr>
<td>power @ 0.25 N [W]</td>
<td>.162</td>
<td>.062</td>
</tr>
<tr>
<td>mov. mass [kg(\times 10^{-3})]</td>
<td>2.8</td>
<td>14</td>
</tr>
<tr>
<td>emc</td>
<td>mean</td>
<td>negligible</td>
</tr>
</tbody>
</table>
Magnetostatic Results II
Shaping the Ferromagnetic Material to Focus B
2 force cases
- rms turb. corr. force \( f_c = 0.363 \text{ N} \)
- max dyn. force \( f_m = 1.27 \text{ N} \)

**active**
- \( \Delta T_{coolant} = 0 \) gives the lowest \( \Delta T \)

<table>
<thead>
<tr>
<th>force</th>
<th>max surface ( \Delta T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_c )</td>
<td>0.10 K</td>
</tr>
<tr>
<td>( f_m )</td>
<td>0.35 K</td>
</tr>
</tbody>
</table>

**passive**
- The (rare) \( f = f_m \) gives out-of-specs \( \Delta T \)

<table>
<thead>
<tr>
<th>force</th>
<th>max surface ( \Delta T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_c )</td>
<td>0.64 K</td>
</tr>
<tr>
<td>( f_m )</td>
<td>2.24 K</td>
</tr>
</tbody>
</table>
Fluid Dynamics Results II

The Active Surface $\Delta T$

![Image of fluid dynamics results](image-url)
Fluid Dynamics Results III
The Passive Surface $\Delta T$
Fluid Dynamics Results IV

\( f = f_m \): the Active and Passive Air Velocities
Running the preliminary tests

- The mechanics is OK
- $\epsilon \approx \frac{1}{2}$ of the design value (maybe a bad coil filling factor and stator part mismatching)
Lessons Learned & Future Work

$\epsilon_{\text{Iron+Copper}} > \epsilon_{\text{PM+Copper}}$

- but (Cons)
  - larger moving mass
  - mechanical contact
  - much larger statoric mass

- and (Pros)
  - low flux leakage
  - heat removal by natural convection

On the way & Still to do

- 2d SM
- 2d Multiphysics
- 2d Multiphysics
- 3d Multiphysics
- 3d E/M & E/S

$\Delta$m dynamics may degrade
tighter tolerances
just higher costs
negligible emc
simpler design
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- 3d Multiphysics
- 3d E/M & E/S
- better bnd conditions @ bottom
- add $\dot{Q}$ from electronics boards
- actuator interaction

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actuator interaction

2d SM thermal deformations
2d Multiphysics better bnd conditions @ bottom
add \( \dot{Q} \) from electronics boards
actuator interaction

3d Multiphysics
3d E/M & E/S

- Magnetostatics
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- 3d Multiphysics
- 3d E/M & E/S
- better bnd conditions @ bottom
- add $\dot{Q}$ from electronics boards
- actuator interaction
- 2d SM thermal deformations
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**Results**
- Experimental Validation

**Summary**
- Novel AO Act
  - Del Vecchio,
  - Biasi,
  - Riccardi,
  - Gallieni

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**The Actuator**
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Lessons Learned & Future Work

\[ \epsilon_{\text{Iron} + \text{Copper}} > \epsilon_{\text{PM} + \text{Copper}} \]

- **Cons**
  - larger moving mass
  - mechanical contact
  - much larger statoric mass

- **Pros**
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- DM dynamics may degrade
  - tighter tolerances
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- Heat transfer
- Fluid dynamics
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The Design Drivers

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Application

Modes

Magnetostatics

Heat transfer

Fluid dynamics

Results

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Summary

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Del Vecchio, Biasi, Riccardi, Gallieni

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The AO Principle
The Design Drivers
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The Multiphysics
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Del Vecchio, C. Biasi, R. Gallieni, D. Riccardi, A. and Spairani, R.

Actuating the Deformable Mirror: a Multiphysics Design Approach
