Wind Effect and its Compensation for Large Reflector Antennas

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Outline

- Motivation
- Wind Effect Analysis
- Control Compensation
- Mechatronics Design
- Conclusions
Outline

Motivation

Wind Effect Analysis

Control Compensation

Mechatronics Design

Conclusions
Motivation

Advantages
- Narrow beam
- High gain

Applications
- Radio astronomy
- Satellite communication
- Deep space exploration
  ...

Large reflector antenna
Green Bank Telescope, 2008
D: 100 × 110m/100MHz-115GHz

- Higher gain
- Better resolution

Larger reflector
Higher working frequency

Higher pointing accuracy

Pointing Accuracy Requirement:
4 arcseconds
Motivation

Higher gain
Better resolution

Larger reflector
Higher working frequency

Larger windward area → Disturbance ↑
More flexible → Oscillation ↑
More sensitive to deformation

Higher pointing accuracy

The required pointing accuracy could be satisfied only when there is no wind!
Motivation

Higher gain
Better resolution

Larger reflector
Higher working frequency

Higher pointing accuracy

Radome

Angular displacement
Decrease its gain
High cost, size limitation

Most Large Reflector Antennas work in open air
Motivation

Higher gain
Better resolution

Larger reflector
Higher working frequency

Higher pointing accuracy


Motivation

- Higher gain
- Better resolution

- Larger reflector
- Higher working frequency

- Higher pointing accuracy

Wind torque
Wind pressure

Compensation
Motivation

Higher gain
Better resolution

Larger reflector
Higher working frequency

Higher pointing accuracy

Compensation

66m S/X band antenna

Operation condition: wind speed of 10m/s
Rotation angle error: 29.52arcsec (RMS)
Flexible pointing error: 21.96arcsec (RMS)
Total pointing error: 32.76arcsec (RMS)
Motivation

- Higher gain
- Better resolution

Larger reflector
- Higher working frequency

Higher pointing accuracy

Compensation

Mars
- 42,586 kilometers
- 400 million kilometers
- 21.96 arcsec

Pointing error caused by deformation
Motivation

- Higher gain
- Better resolution

Larger reflector
Higher working frequency

Higher pointing accuracy

Mars
42,586 kilometers

400 million kilometers

Pointing error caused by deformation

Analysis Compensation

Open Problem
Outline

Motivation

Wind Effect Analysis

Control Compensation

Mechatronics Design

Conclusions
Rigid model

Advantage: Lower order
Disadvantage: Without any flexible information

※ That’s why the pointing error caused by flexible deformation could not be compensated with those proposed methods.
Wind Effect Analysis

Traditional

- **Rigid model**
  - Advantage: Lower order
  - Disadvantage: Without any flexible information

- **Finite element model**
  - Advantage: Describing flexible oscillation
  - Disadvantage: Too much degree of freedom
Wind Effect Analysis

Pointing Control – Oriented Model

Rigid model: \( T = J\ddot{\theta} + D_r\dot{\theta} \)  
Flexible model: \( M\ddot{q} + D\dot{q} + Kq = B_0u \)  
\( y = C_{oq}q + C_{ov}\dot{q} \)  
\( q = \Phi q_m \).

\[
\begin{bmatrix}
J & 0 \\
B_1 \cdot J & M_m
\end{bmatrix}
\begin{bmatrix}
\ddot{\theta} \\
\ddot{q}_m
\end{bmatrix} +
\begin{bmatrix}
D_r & 0 \\
B_1 \cdot D_r & D_m
\end{bmatrix}
\begin{bmatrix}
\dot{\theta} \\
\dot{q}_m
\end{bmatrix} +
\begin{bmatrix}
0 & 0 \\
0 & K_m
\end{bmatrix}
\begin{bmatrix}
\theta \\
q_m
\end{bmatrix} =
\begin{bmatrix}
T_1 \\
0
\end{bmatrix} +
\begin{bmatrix}
0 & F
\end{bmatrix}
B_{12}
\]

\( y = C_{mq}q_m \)

Nodes displacements could evaluate the deformation of the structure
Wind Effect Analysis

- Analyze the extent of the pointing impact of all its vibration mode

- Traditional
  - Antenna Structure Model
  - PCOM

- Model reduction
  - Keep the Most Significant Modes
  - Ignore the Least Significant Modes

PCOM
Wind Effect Analysis

Traditional

Antenna Structure Model

PCOM

FE Modeling  Model Calibration  PCOM construction
Wind Effect Analysis

**FE Modeling**

<table>
<thead>
<tr>
<th>Test content</th>
<th>Load (Kg)</th>
<th>Test results (Hz)</th>
<th>Simulation results (Hz)</th>
<th>Relative error</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>6.84</td>
<td></td>
<td>7.30</td>
<td>6.72%</td>
</tr>
<tr>
<td>100</td>
<td>6.84</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Model Calibration**

**Natural Frequency**

<table>
<thead>
<tr>
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<th>Load (Kg)</th>
<th>Test results (Hz)</th>
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</tr>
</tbody>
</table>

**PCOM construction**

**Deformation**

<table>
<thead>
<tr>
<th>Test content</th>
<th>Load (Kg)</th>
<th>Test results (mm)</th>
<th>Calculate results (mm)</th>
<th>Relative error</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>-0.677</td>
<td></td>
<td>-0.743</td>
<td>9.74%</td>
</tr>
<tr>
<td>100</td>
<td>-1.679</td>
<td></td>
<td>-1.566</td>
<td>6.73%</td>
</tr>
</tbody>
</table>

| 50           | -0.506    |                   | -0.532                 | 5.13%          |
| 100          | -1.236    |                   | -1.163                 | 5.91%          |
Wind Effect Analysis

FE Modeling
- Main reflector Deformation
- Feed displacement

Model Calibration
- Sub-reflector displacement
- Sub-reflector rotation

PCOM construction

Traditional

Antenna Structure Model

PCOM

The 1st order

The 2nd order

The 3rd order

<table>
<thead>
<tr>
<th>Order</th>
<th>Energy ratio</th>
<th>Pointing error in AZ(°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.248</td>
<td>$7.08 \times 10^{-4}$</td>
</tr>
<tr>
<td>2</td>
<td>0.395</td>
<td>$3.56 \times 10^{-3}$</td>
</tr>
<tr>
<td>3</td>
<td>0.008</td>
<td>$4.90 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

0.08% 9.4%
**Wind Effect Analysis**

The shaft rotation angle is given by:

$$\theta_p = \theta + \theta_n = \theta + \sum_{i=1}^{k} F_i G_i$$

Where:
- $\theta_p$ is the total shaft rotation angle.
- $\theta$ is the initial shaft rotation angle.
- $\theta_n$ is the shaft rotation angle caused by deformation.
- $F_i$ is the wind force.
- $G_i$ is the pointing error caused by each mode.

**Modeling Steps**:
- FE Modeling
- Model Calibration
- PCOM Construction

**Equation**:

$$G_i = \left( A^{-1} \sum_{s=1}^{5,i} G_{si} u_s + A^{-1} \sum_{s=1}^{5,2} G_{si} v_s + A^{-1} \sum_{s=1}^{5,3} G_{si} w_s + A^{-1} \sum_{s=1}^{5,4} G_{si} \right)$$

$$+ L_2 \left( A^{-1} \sum_{s=1}^{5,i} G_{si} u_s + A^{-1} \sum_{s=1}^{5,2} G_{si} v_s + A^{-1} \sum_{s=1}^{5,3} G_{si} w_s + A^{-1} \sum_{s=1}^{5,4} G_{si} \right) (L_i + L_3)$$

$$- (A^{-1} \sum_{s=1}^{5,i} G_{si} u_s + A^{-1} \sum_{s=1}^{5,2} G_{si} v_s + A^{-1} \sum_{s=1}^{5,3} G_{si} w_s + A^{-1} \sum_{s=1}^{5,4} G_{si})$$

$$- (G_{ib} + G_{ib}) + G_{in} + L_2 G_{ib} \left( \frac{1}{M} + L_3 G_{ib} \right)$$

**Pointing error**:
- Caused by feed
- Caused by sub-reflector
- Caused by main reflector

**K_w / f**
**Wind Effect Analysis**

### FE Modeling

- **Max deformations under a 10m/s wind speed**
  - Main reflector rotation (deg): $2.66 \times 10^{-3}$
  - Displacement of the vertex (m): $0.88 \times 10^{-5}$
  - Displacement of the feed (m): $-0.55 \times 10^{-5}$
  - Displacement of the sub-reflector (m): $0.50 \times 10^{-4}$
  - Sub-reflector rotation (deg): $-4.48 \times 10^{-4}$

### Model Calibration

- **FEM → Deformed Reflector → GRASP**

### PCOM construction

- **PCOM**
- **GRASP**
- **Relative error**
  - Pointing error: 0.0041°, 0.0043°, 4.6%
Wind Effect Analysis

FE Modeling | Model Calibration | PCOM construction

Traditional

Antenna Structure Model

PCOM

Wind torque and force almost have the same impact on pointing error

FPE: Flexible pointing error
RPE: Rotation error
TPE: Total pointing error

Outline

Motivation

Wind Effect Analysis

Control Compensation

Mechatronics Design

Conclusions
Passive Compensation

Traditional control method and improved PID:

Disadvantage: flexible formation induced pointing error was neglected.

Traditional pointing servo control

Disturbance Observer

- Estimating disturbance or overall pointing error
- Based on LQG
- Based on predictive control

Feedforward compensation directly

Deriving a optimal control action

Estimating disturbance and Pointing error for gust
Passive Compensation

Based on DOB | Based on LQG | Based on MPC

Disturbance Observer (DOB) → Estimating the overall disturbance (Wind induced torque/force, Model perturbation, Nonlinear Components)

Wind Force $F$ → $G_f$

Wind Torque $T$ → $G_t$

$G_m^{-1}$

$G_c$

$G_t^{-1}$

$Q_d$

$\hat{T}_d$

$T_m$

$T_w$

$u_d$

$Ref$

Beam pointing
Linear-Quadratic-Gaussian (LQG)

LQG control system based on the PCOM.

$K_c$: optimal feedback gain matrix

$K_e$: optimal estimator gain matrix

Jie Zhang, Jin Huang* and Jun Zhou et al., A compensator for large antennas based on pointing error estimation under a wind load, *IEEE Trans. Control systems technology*, accepted.
Passive Compensation

<table>
<thead>
<tr>
<th>Based on DOB</th>
<th>Based on LQG</th>
<th>Based on MPC</th>
</tr>
</thead>
</table>

Model Predictive Control (MPC) → Reject the disturbance of gust

Conventional method
Passive Compensation

- Based on DOB
- Based on LQG
- Based on MPC

Model Predictive Control (MPC) → Reject the disturbance of gust

Estimating disturbance with wind field sensing
Passive Compensation

Based on DOB  Based on LQG  Based on MPC

Model Predictive Control (MPC) ➔ Reject the disturbance of gust

Wind force $F$

Wind torque $T$

PCOM

Pointing $Y_k$

Integral control

Velocity controller

Motor and Reducer

State observer

Model predictive control

Wind force and torque estimation

LSSVR

Wind speed

Ref

$T_m$

$\hat{x}_k$

$\theta_{yc}$

$G_f$

$G_t$

$G_f$

$G_t$
Passive Compensation

Based on DOB | Based on LQG | Based on MPC

Model Predictive Control (MPC) → Reject the disturbance of gust

Sampling point wind speed

The comparison between test speed and the prediction speed
Simulation results with 7.3m Antenna

<table>
<thead>
<tr>
<th>Control method</th>
<th>Max pointing error (°)</th>
<th>RMS pointing error (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PID</td>
<td>0.0112</td>
<td>0.0042</td>
</tr>
<tr>
<td>DOB</td>
<td>0.0030</td>
<td>0.0014</td>
</tr>
<tr>
<td>LQG</td>
<td>0.0024</td>
<td>0.0008</td>
</tr>
<tr>
<td>MPC</td>
<td>0.0018</td>
<td>0.0006</td>
</tr>
</tbody>
</table>

DOB: 73.3% 66.6%
PID: 79.7% 81.9%
LQG: 84.8% 85.8%
Passive Compensation

Simulation results with 7.3m Antenna

In initial stage

<table>
<thead>
<tr>
<th>Control method</th>
<th>Max pointing error(°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PID</td>
<td>0.0161</td>
</tr>
<tr>
<td>DOB</td>
<td>0.0049</td>
</tr>
<tr>
<td>LQG</td>
<td>0.0033</td>
</tr>
<tr>
<td>MPC</td>
<td>0.0016</td>
</tr>
</tbody>
</table>

51.5%
Outline

Motivation

Wind Effect Analysis

Control Compensation

Mechatronics Design

Conclusions
Active Compensation

66m Beam Waveguide Antenna

- Moment of Inertia: $2.14 \times 10^9$ kg·m²
- Fundamental frequency: 2.1 Hz
- Bandwidth of servo system: 0.6 Hz

Performance for compensating high frequency pointing error

- Improving the pointing accuracy

Adjustable Plate Mirror

Electric cylinder

Motor

Mirror

Axis of elevation compensation

Axis of azimuth compensation
Active Compensation

Real-time Pointing Error Compensation System (RPECS)

Sub-reflector

Main reflector

Focal axis

Pitch axis

Beam waveguide system
The primary servo subsystem is used to compensate the large-range and slowly-varying error. The subsystem is used to compensate the final pointing errors with high frequency components.
The comparison of the bandwidth between the primary servo and the APM servo
The compensation effect under a wind speed of 10m/s:

![Graph showing compensation effect](image_url)

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<th>Control method</th>
<th>Max pointing error (°)</th>
<th>RMS pointing error (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPID</td>
<td>0.0368</td>
<td>0.0091</td>
</tr>
<tr>
<td>RPECS</td>
<td>0.0020</td>
<td>0.00067</td>
</tr>
</tbody>
</table>

Meet the requirement

94.6%  92.7%

The wind effect on pointing accuracy for large antenna is analyzed, and a pointing control-oriented model is presented.

Several Passive pointing error compensation is proposed, which improve the pointing performance effectively.

An active compensation method is put forwarded, in which the high frequency disturbance can be rejected with a fast and high accuracy plate mirror.

These wind disturbance compensation methods can be applied to newly developed large reflector antennas and control system upgrading for those in operation with a low cost hardware, for an improved pointing performance.
Thank you!