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Optimization of Multi-Loop On Glass Vehicle Antennas for Panoramic Sun-Roof

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Introduction

Antenna background

Motivation
Antenna background

Common 4 types of car antenna

- **Internal antenna**
  - On-glass antenna
- **External antenna**
  - Pole antenna
  - Micro antenna
  - Shark-fin antenna

<table>
<thead>
<tr>
<th>Type</th>
<th>Internal antenna</th>
<th>External antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantages*</td>
<td>• Low cost</td>
<td>• High efficiency</td>
</tr>
<tr>
<td></td>
<td>• Robustness from external shocks</td>
<td>• Large bandwidth</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Less influence from the shape of car body</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>• Low efficiency</td>
<td>• Exposure to the exterior of car body</td>
</tr>
<tr>
<td></td>
<td>• Narrow frequency band</td>
<td>• Extra installation cost</td>
</tr>
<tr>
<td></td>
<td>• Performance is influenced by car body</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Driver visibility disturbance</td>
<td></td>
</tr>
</tbody>
</table>

By using optimization, design on-glass antenna overcome its disadvantages

Antenna background

- **Antenna**
  - **Electrical device** which converts electric power into radio waves or radio waves into electric power
  - So radio waves are radiated/received by means of transmitting/receiving antennas

- **S parameter** (Scattering parameter)
  - Describes the input to output relationship between ports
    - \[
      \begin{bmatrix}
        v_1^- \\
        v_2^-
      \end{bmatrix}
      =
      \begin{bmatrix}
        S_{11} & S_{12} \\
        S_{21} & S_{22}
      \end{bmatrix}
      \begin{bmatrix}
        v_1^+ \\
        v_2^+
      \end{bmatrix}
    \]
    - \[S_{ij} = \left. \frac{v_j^-}{v_i^+} \right|_{v_k^+=0,k\neq i}\]
  - Example
    - If radiated 60%, \( S_{11} = \frac{v_j^-}{v_i^+} = \frac{40}{100} = -3.98 \text{dB} \)
Antenna background

- **Frequency band**
  - All waveforms are actually just sum of simple sinusoids of different frequencies
  - **Frequency bands** are different depending on purpose of use

<table>
<thead>
<tr>
<th>Service</th>
<th>Typical Frequency</th>
<th>Tx</th>
<th>Rx</th>
<th>Direction of Radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM Radio</td>
<td>Approximately 1 MHz</td>
<td></td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>FM Radio</td>
<td>88 MHz to 108 MHz</td>
<td>Yes</td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>In-vehicle TV</td>
<td>30 MHz to 400 MHz</td>
<td>Yes</td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>Digital Audio Broadcasting (DAB)</td>
<td>100 MHz to 400 MHz</td>
<td>Yes</td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>Remote Keyless Entry (RKE)</td>
<td>315 MHz/415 MHz/434 MHz</td>
<td>Yes</td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>Tyre Pressure Monitoring System (TPMS)</td>
<td>315 MHz/415 MHz/434 MHz</td>
<td>Yes</td>
<td>Yes</td>
<td>Intra-vehicular</td>
</tr>
<tr>
<td>Cellular Phone</td>
<td>850 MHz</td>
<td>Yes</td>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>(provision of Internet via HSFA)</td>
<td>900 MHz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1800 MHz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1900 MHz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2100 MHz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Satellite Navigation (GPS)</td>
<td>1.575 GHz</td>
<td>Yes</td>
<td></td>
<td>Satellite</td>
</tr>
<tr>
<td>Satellite Digital Audio Radio Service (SDARS)</td>
<td>2.3 GHz</td>
<td>Yes</td>
<td></td>
<td>Satellite</td>
</tr>
</tbody>
</table>

Summary of signals used on modern and next generation vehicles


Motivation

- Among various electromagnetic waves vehicle receives, the **FM radio** frequency band has the **longest wavelength**
- Since required **antenna's length** is usually **proportional to wavelength**, it is difficult to miniaturize antenna for FM radio*
- So antenna for FM radio should be designed as **internal(on-glass) antenna**, rather than external antenna
- Additionally, to maximize **space efficiency**, design antenna shape as **multi-loop** structure

- Selected design area is panoramic sun-roof, because
  - Doesn’t interfere with **driver’s sight (Safety)**
  - Has **sufficient** feasible design area (Applicability)

Design **multi-loop on-glass antenna over panoramic sun-roof**

EM analysis

Initial modeling

Process

Result
Initial design

• Share a portion for space efficiency
  • 80MHz : outer loop length 2m
  • 107MHz : mid loop length 1.4m
  • 130MHz : inner loop length 0.9m
Design types _ port location depending on y direction

**Type A**
- Feed on left back feasible region

**Type B**
- Feed on left front feasible region

- Car body has influence on the performance of the antenna, sort design to type A and B
- Since it is symmetrical with respect to vehicle axial direction, **not consider mirror shape**
Process

- For more than 3000 meshes, maintain accuracy above 85%.
  - # of car body mesh = near 3000

- Requests: S-parameter
  - Interest frequency band: 88MHz ~ 108 MHz (88,93,98,103,108 MHz)
  - Port impedance: 50 Ohm

- For view transparency
  - Mid & inner loop wire radius: 0.25 mm
  - Outer loop wire radius: 1 mm

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Case study _ type A

**Case 1**
Edge of car frame

**Case 2**
Quarter of car frame

**Case 3**
Middle of car frame

Based on the tendency of s parameter and impedance value, decided to design case 1 and case 2.
Case study _ type B

Based on the tendency of s parameter and impedance value, decided to design case 2 and case 3
Antenna optimization

- Define formulation
- DoE & fitting
- Optimization

Analysis result ➔ New design variables

FEKO: Comprehensive Electromagnetic Solutions

HyperStudy
Flowchart

Initial Antenna Parameter

\[ \begin{bmatrix} w_i \\ h_i \end{bmatrix} \]

Formulation

| Objective function | \( \min \{ \text{mean} f_i(S_{11}) \} \)  
| : | \( f_i = \{ 88, 93, 98, 103, 108 MHz \} \) |
| Design variables | \( w_i : \text{width of each loop (} i = 1, 2, 3 \)  
| : | \( h_j : \text{height of each loop (} j = 1, 2, 3 \) |
| Constraint | \( \max(S_{11}) \leq \text{specific value} \)  
| : | \( 0 < h_1 < h_2 < h_3 < 1.6 \)  
| : | \( 0 < w_1 < w_2 < w_3 < 0.9 \) |

Surrogate Model-based Design Optimization (SMBDO)

Optimum Antenna Parameter

\[ \begin{bmatrix} w_{opt} \\ h_{opt} \end{bmatrix} \]

Design of Experiments & Fitting

DoE (LHD)

Fitting (HK)

Design the Difference with Digital twin
Formulation

Minimize $\mathbf{x}$

Subject to

Mean ($S_{11}$)

Max ($S_{11}$) $\leq S_{11}^{target}$

$0 < x_1 < x_2 < x_3 < 0.9$

$0 < x_4 < x_5 < x_6 < 1.6$

$x_L \leq \mathbf{x} \leq x_U,$ $\mathbf{x} \in \mathbb{R}^{N_{dv}}$

$S_{11}^{target} = -3^*$

• Feasible region
  • The front of the sunroof can be moved
  • To reduce the possibility of preventing the resonance effect of the antenna

Surrogate model

• Purpose: to reduce computation time and costs
• Surrogate model
  • RSM (Response surface model)-regression model using least square method
    • Easy to use, implementation is simple, suitable for real experiments
  • Kriging model-interpolation model HyperKriging (HK)
    • Implementation is complex, suitable for deterministic computational experiment

• Since it is a model generated by interpolation, greatly affected by selection of the experiment point

Kriging model (blue line) and true function (red line) ➔ Bad space filling
Kriging model (blue line) and true function (red line) ➔ Good space filling
Design of Experiments (DoE)

- Evaluate with **Latin-Hypercube design (LHD)**
  - Saturated points #, \( n_{SAT} = \frac{(NDV+1)(NDV+2)}{2} = \frac{(6+1)(6+2)}{2} = 28 \)
    - where NDV: # of design variables
  - Recommended sampling points # = \( 2 \times n_{SAT} \sim 4 \times n_{SAT} \)
  - Because it is a nonlinear reaction that influence of car body and Sequential sampling impossible in Hyperstudy post-processing
    # of sampling point : 112 (4 \times n_{SAT})

- **LHD**
  - Developed by Mckay in 1979
  - Randomly sampling only one sample point at each level
    - Optimum LHD (OLHD)
      - Sample points are spread out using optimization
      - Space-filling properties satisfied.
    - Optimality criteria
      - Maximin distance
      - Entropy maximize
Correlation coefficient _ Type A. case 1

- Correlation coefficient
  - Understand affects between each factor and responses. if they are influencing each other, obtain the affect tendency.

**Type A. case 1**

- Positive correlation

---

Design the Difference with **Digital twin**

ATC 2017
Correlation coefficient _ Overall

Type A

Case 1

Case 2

Case 3

Type B

Case 1

Case 2

Case 3

Outer loop's width length is identified important value compared to others
Fitting _ validation

Cross validation

**Leave-one-out Cross Validation (LOOCV)**
Input data broken into n group, validation for a new approximate model using n-1 group’s data

**Root Mean Square Error (RMSE)**
A higher quality fit will have a lower value

\[ CV_n = \sqrt{\frac{1}{n} \sum_{i=1}^{n} [Y_i - \bar{Y}_i]^2} \]

<table>
<thead>
<tr>
<th>Type A</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>0.0215</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.0417</td>
</tr>
<tr>
<td>Case 3</td>
<td>0.0477</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type B</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>0.0197</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.1143</td>
</tr>
<tr>
<td>Case 3</td>
<td>0.0920</td>
</tr>
</tbody>
</table>

- All kriging model is created with 112 samples
- In order to further improve the accuracy of the kriging model, it is necessary to further extend the number of sampling points
Optimization

- Optimization
  - Formulation
    - Find: each loop’s width, height
    - To minimize: mean \( S_{11} \)
    - Subject to \( \max(S_{11}) \leq \text{goal value} \)
    - Goal value = \(-3 \rightarrow 50\% \text{ radiation}\)

- Optimization specifications
  - Algorithm: ARSM (Adaptive Response Surface Method)
  - Maximum iterations: 50
  - Solver: SQP
  - Absolute convergence: 0.001
  - Move limit fraction: 0.15
### Overall result

<table>
<thead>
<tr>
<th>Type A</th>
<th>Type B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Case 1</strong></td>
<td><strong>Case 2</strong></td>
</tr>
<tr>
<td><strong>Case 2</strong></td>
<td><strong>Case 3</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Response</th>
<th>Initial</th>
<th>Optimum</th>
<th>Response</th>
<th>Initial</th>
<th>Optimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (S_{11})</td>
<td>-2.115</td>
<td>-2.938</td>
<td>Mean (S_{11})</td>
<td>-2.851</td>
<td>-4.468</td>
</tr>
<tr>
<td>Max (S_{11})</td>
<td>-1.695</td>
<td>-2.396</td>
<td>Max (S_{11})</td>
<td>-1.284</td>
<td>-1.982</td>
</tr>
<tr>
<td>Mean (S_{11})</td>
<td>-5.262</td>
<td>-9.542</td>
<td>Mean (S_{11})</td>
<td>-4.859</td>
<td>-8.618</td>
</tr>
<tr>
<td>Max (S_{11})</td>
<td>-2.796</td>
<td>-5.668</td>
<td>Max (S_{11})</td>
<td>-3.695</td>
<td>-6.892</td>
</tr>
</tbody>
</table>

- Two models that satisfy the constraint among the six models are **Case 2 and 3 of Type B**
- Almost design variables converged to LB or UB
Result _ type B

Type B _ Case 2 (ported quarter of car frame)

Type B _ Case 3 (ported middle of car frame)

-6dB

80Ω
Conclusion

Summary

Proposal
## Result summary

<table>
<thead>
<tr>
<th>Design</th>
<th>Response</th>
<th>Initial design</th>
<th>Optimum design</th>
<th>Radiation Improved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type B</td>
<td>Mean($S_{11}$) (Radiation rate)</td>
<td>-5.262 (70%)</td>
<td>-9.542 (89%)</td>
<td>19%↑</td>
</tr>
<tr>
<td>Case 2</td>
<td>Max($S_{11}$) (Radiation rate)</td>
<td>-2.796 (47%)</td>
<td>-5.668 (73%)</td>
<td>26%↑</td>
</tr>
<tr>
<td>Type B</td>
<td>Mean($S_{11}$) (Radiation rate)</td>
<td>-4.859 (67%)</td>
<td>-8.618 (86%)</td>
<td>19%↑</td>
</tr>
<tr>
<td>Case 3</td>
<td>Max($S_{11}$) (Radiation rate)</td>
<td>-3.695 (57%)</td>
<td>-6.892 (80%)</td>
<td>23%↑</td>
</tr>
</tbody>
</table>

- From the antenna design model of all 6 cases, the models finally satisfying the constraint are [Type B. case2] and [type B. case3]
- All of the two models improved on the S parameter
  - Mean($S_{11}$): both **improved by 19%**
  - Max($S_{11}$): **improved by 26% & 23%**
• Shows the Mean ($S_{11}$) of **0.1% variation** of only one variable for each design variable for Type B. Case2 antenna

• As the result of the above-described sensitivity analysis, the **tendency of Mean ($S_{11}$)** tends towards the direction in which each variable converged

• We propose that designers determine **dimension of multiple loops** with reference to the above trends
Summary

- Antenna performance remarkably improved with **FEKO** and **HyperStudy**

<table>
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<th>FEKO</th>
<th>HyperStudy</th>
</tr>
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<tr>
<td>Antenna modeling</td>
<td>DoE &amp; Fitting</td>
</tr>
<tr>
<td>EM analysis</td>
<td>Optimization</td>
</tr>
</tbody>
</table>

- Adjusted **position** and **size** to improve antenna performance and **solved shortcomings** of on-glass antenna

- **The mesh number** was determined in consideration of analysis time

- Considering time (cost), optimized through **surrogate model based optimization, optimization algorithm (ARSM)** are selected
Thank you