Target Cascading: A Design Process For Achieving Vehicle Targets

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Overview

• Systems Engineering and Target Cascading
• Hierarchical Optimization for Target Cascading
• Target Cascading Application to SUV Design
• Analysis Model Description
• Results and Future Work
Systems Engineering: Why Important?

Large-scale design

Consistent design? Efficient process?

Design Targets

Dynamics | NVH | Durability | Safety
• Definitions (IEEE Standard 1220)
  
  - ... The Systems Engineering Process is a generic problem-solving process, which provides the mechanisms for identifying and evolving the product and process definitions of a system. ...

• A Hierarchical System Terminology (NASA)
  
  Supersystem
  System
  Element
  Subsystem
  Assembly
  Subassembly
  Part
Target Cascading in Systems Engineering

• Target Cascading enables quick target setting at the early stages of the system design process.
Two Approaches to Target Cascading

Component Approach
- Component
- Subsystem
- System
- Supersystem

Systems Approach
- Component
- Subsystem
- System
- Supersystem

Issues:
- Complexity
- Design availability
- Design freedom

Issues:
- Efficiency
- Design Feasibility
- Common Variables
- Model Availability
Target Cascading Problem Statements

• Given
  - a set of overall (supersystem) targets,
  - models for systems, subsystems and components,

• Determine system, subsystem and component targets by
  - partitioning the overall design problem,
  - satisfying feasibility/optimality of system, subsystem and component designs,
  - achieving overall targets.
Hierarchical Target Cascading Structure

- Target Cascading structure is composed of multiple levels.
- Linking variables and responses are identified.

Supersystem Optimal Design Model

System Optimal Design Model

Subsystem Optimal Design Model

Analysis Model

Analysis

Analysis

Analysis

Analysis

Analysis

Analysis

Analysis

Analysis

Analysis

Analysis

Analysis
Design vs. Analysis Models

• Design Models
  - Call for analysis models to make design decisions.
  - Are composed of design objective and constraints.
  - Can call multiple analysis models.

• Analysis Models
  - Take input design variables, parameters, and low-level responses.
  - Return responses for current design.
  - Are explicit functions, response surface models, simulations, or spreadsheets.
Hierarchical Optimization

Vehicle Targets

Minimize Deviation between vehicle targets and responses
subject to constraints for system responses, subsystem linking variables and vehicle

Minimize Deviation between system targets and responses and between subsystem linking variable targets and variables
subject to constraints for subsystem responses, component linking variables and system

Minimize Deviation between subsystem targets and responses and between component linking variable targets and variables
subject to constraints for subsystem
Optimal design problem at $i^{th}$ level for $j^{th}$ partitioned element minimizes the deviations for responses and linking variables from the upper level $U$ subject to responses and linking variables from the lower level $L$.

Minimize $\tilde{x}_{(i+1)j}, y_{(i+1)j}, R_{(i+1)j}$ $\left\| R_{ij} - R_{ij}^U \right\| + \left\| y_{(i+1)j} - y_{(i+1)j}^U \right\| + \varepsilon_R + \varepsilon_y$

where $R_{ij} = r_{ij\leftrightarrow(i+1)j}(R_{(i+1)j}, \tilde{x}_{(i+1)j}, y_{(i+1)j})$

subject to

$\left\| R_{(i+1)j} - R_{(i+1)j}^L \right\| \leq \varepsilon_R$

$\left\| y_{(i+2)j} - y_{(i+2)j}^L \right\| \leq \varepsilon_y$

$g_{ij\leftrightarrow(i+1)j}(R_{(i+1)j}, \tilde{x}_{(i+1)j}, y_{(i+1)j}) \leq 0$

$h_{ij\leftrightarrow(i+1)j}(R_{(i+1)j}, \tilde{x}_{(i+1)j}, y_{(i+1)j}) = 0$
Application to Vehicle Design

- **Vehicle - production SUV**
  - Targets - heuristic ride and handling metrics

- **Emphasis**
  - Formal Target Cascading problem statement
  - Demonstration of T.C. potential to identify / study
    - Possible design goal incompatibilities
    - Compromise among competing objectives

- **Goals for example problem**
  - Meaningful, yet of manageable scope
  - Vehicle, system, and component levels; linking variables
Problem Schematic

VEHICLE OPTIMAL DESIGN PROBLEM
\[ \mathbf{T} = [\omega_{sf}, \omega_{sr}, \omega_{tf}, \omega_{tr}, \omega_p, k_{us}]^T \]

VEHICLE LEVEL

SYSTEM LEVEL

COMPONENT LEVEL

FRONT SUSPENSION
- SUSP. STIFFNESS
- SPRING STIFFNESS
- FRONT COIL SPRING

REAR SUSPENSION
- SUSP. STIFFNESS
- SPRING STIFFNESS
- REAR COIL SPRING

TIRE VERTICAL STIFFNESS
- FRONT, REAR TIRE STIFFNESS
- INFLATION PRESSURES

TIRE CORNERING STIFFNESS
- FRONT, REAR CORNERING STIFFNESS
Vehicle: Linear Half-Car Model

Vertical

Targets

- Front and rear ride frequencies $\omega_{sf}$, $\omega_{sr}$
- Pitch natural frequency $\omega_p$
- Wheel hop frequencies $\omega_{tf}$, $\omega_{tr}$

Variables / Responses

- Front and rear suspension, tire stiffnesses
- $a$, $b$
Vehicle: Bicycle Model

Lateral

\[
\delta_f = \frac{L}{R} + \left( \frac{mb}{LC_{\alpha f}} - \frac{ma}{LC_{\alpha r}} \right) \frac{u^2}{R}
\]

Targets

- understeer gradient \( k_{us} \)

Variables / Responses

- a, b
- tire cornering stiffness \( C_\alpha \)
Given a required suspension stiffness from the vehicle model,

DOUBLE A-ARM - SUSPENSION

Targets

- suspension stiffness $K_{sf}, K_{sr}$

Variables / Responses

- coil spring stiffness and free length

- multi-body model (Hogland, 00)

- spindle force applied, static deflection predicted
  - $K_{sf}, K_{sr}$
Given a required tire stiffnesses from the vehicle model,

**Vertical Stiffness:**

\[ K_T = 0.9 \left[ (0.1839 \, P_i - 9.2605)F_m + 110119 \right] \]

**Cornering Stiffness:**

\[ C_\alpha = \left[ (-2.668 \times 10^{-6})P_i^2 + (1.605 \times 10^{-3})P_i - 3.86 \times 10^{-2} \right]F_m \]

From Wong, Theory of Ground Vehicles

- **Stiffnesses are a function of**
  - inflation pressure
  - load due to vehicle weight
Component: Suspension Springs

Given a required coil spring properties from the suspension model,

- Use classic spring design equations (e.g. Shigley)
  - Static shear stress
  - Fatigue life
  - Stability

**Targets**

- linear stiffness $K_{LIN}$
- free length $L_0$

**Variables**

- wire diameter, coil diameter, pitch ($d$, $D$, $p$)
\[
\min ||T - R_V|| + \varepsilon_R + \varepsilon_y
\]

Subject to constraints on:

Min., max. \(a\) and \(b\)

Convergence tolerances

\[
\|R_S - R_S^L\| \leq \varepsilon_R
\]

\[
1/2(||y_{SS} - y_{SS3}^L|| + ||y_{SS} - y_{SS4}^L||) \leq \varepsilon_y
\]

\[
\tilde{x}_s = \begin{cases} a \\ b \end{cases}
\]

\[
R_S = \begin{bmatrix} K_{SF} \\ K_{SR} \\ K_{TF} \\ K_{TR} \\ C_{oF} \\ C_{oF} \end{bmatrix}
\]

\[
R_V = \begin{bmatrix} \omega_{SF} \\ \omega_{SR} \\ \omega_{TF} \\ \omega_{TR} \\ \omega_P \\ k_{US} \end{bmatrix}
\]

To / from front susp’n

To / from rear susp’n

To / from tire \(C_{\alpha}\) model

To / from tire \(K_t\) model

\(T\) = target vector (given)

\(R_V\) = target values from vehicle model

\(R_S\) = responses from system models

\(y_{SS}\) = linking variables (tire pressures)
Problem Setup

- Set constraints and bounds at each level, e.g.,
  - Fully laden static deflection (vertical and pitch)
  - Maximum allowable suspension travel
  - Spring dimensions

- Select targets based on ride/handling experience

- Initially, try to please everybody
  - Weight all targets equally in objective function
## Results - First Run

<table>
<thead>
<tr>
<th>Vehicle Targets</th>
<th>Targets</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ride frequency</td>
<td>1.20 [Hz]</td>
<td>1.11</td>
</tr>
<tr>
<td></td>
<td>1.44 [Hz]</td>
<td>1.55</td>
</tr>
<tr>
<td>Wheel hop freq.</td>
<td>12.00 [Hz]</td>
<td>11.55</td>
</tr>
<tr>
<td></td>
<td>12.00 [Hz]</td>
<td>11.55</td>
</tr>
<tr>
<td>Pitch frequency</td>
<td>0.50 [Hz]</td>
<td>0.87</td>
</tr>
<tr>
<td>Understeer gradient</td>
<td>0.00719 [rad/m/s²]</td>
<td>0.0061</td>
</tr>
</tbody>
</table>

The diagram shows normalized responses for various vehicle targets. "1" represents an exact target match.
## Results – Consistent Design

- Compare $i^{th}$-level target and $i^{th}$-level response
- Linking variables also consistent

<table>
<thead>
<tr>
<th>Variables</th>
<th>Optimal</th>
<th>Lower Bounds</th>
<th>Upper Bounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front susp. stiffness [N/m]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Front tire stiffness [N/m]</td>
<td>36930</td>
<td>13130</td>
<td>56250</td>
</tr>
<tr>
<td>Front cornering stiffness [N/rad]</td>
<td>105500</td>
<td>48100</td>
<td>128800</td>
</tr>
<tr>
<td>K SPRING [N/mm]</td>
<td>120</td>
<td>120</td>
<td>160</td>
</tr>
<tr>
<td>Front susp. stiffness [N/m]</td>
<td>300000</td>
<td>123100</td>
<td>300000</td>
</tr>
<tr>
<td>Front Tire Pressure [kPa]</td>
<td>124.8</td>
<td>83</td>
<td>330</td>
</tr>
<tr>
<td>Front Tire Vert. Stiffness [N/m]</td>
<td>300000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Front Tire Pressure [kPa]</td>
<td>123.35</td>
<td>83</td>
<td>330</td>
</tr>
<tr>
<td>Front Cornering Stiffness [N/rad/m^2]</td>
<td>111000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wire diameter [mm]</td>
<td>24.3</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>Coil Diameter [mm]</td>
<td>200</td>
<td>50</td>
<td>200</td>
</tr>
<tr>
<td>Pitch [mm]</td>
<td>97.2</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>K SPRING [N/mm]</td>
<td>120.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Results

• Not all targets met
  - Suppose Pitch Frequency of 0.87 Hz deemed unacceptable…
  - OPTION A - Decrease target value – try to pull Pitch Frequency down closer to 0.5 Hz
    » Change target value without changing feasible design space

• Results
Results

• Changing target alone has little effect on Pitch Frequency
  - Design decision: expand design space by relaxing constraint/bound
  - Try increasing weight of target in objective function
  - OPTION B – Increase target weight 10x, decrease lower bound on front coil spring stiffness

• Results
Results

• Pitch frequency target not achieved after
  - Increasing its relative importance
  - Relaxing relevant variable bound

• Conclusion
  - Some targets cannot be achieved within current design space.
  - Discussion and decisions by design team required.
    » Change targets?
    » Relax constraints?
    » Relax bounds further?
Discussion and Conclusions

- Target cascading links different software tools, possibly in different locations via Internet
- Designs are concurrent – design targets are updated and communicated to each ‘department’
- TC can unearth target incompatibilities early in design process
Future Work

• Implementation of Target Cascading process in Internet-based design environment

• Expansion of Target Cascading model hierarchy with more analysis models

• Model reduction techniques to achieve proper model fidelity at each level