Robustness Analysis of Medium & HD Engines

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GT-SUITE CONFERENCE
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Outlines

- Background
- Sensitivity analysis
- Probability density and cumulative distribution
- Conclusion
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Illustrating Example:

To minimize $Y$: the optimal solution is reached by dataset $x_1$
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If the tolerances of $x$ are $\Delta x$: $x_1$ is still the robust optimal solution.
**Basics**

- The intent of robust design is to create systems that are *(as far as possible)* insensitive to variations from production, the environment, time and use.
- Illustrating Example:

```
To minimize Y: the optimal solution is reached by dataset x₁
If the tolerances of x are Δx: x₁ is still the robust optimal solution
If the tolerances of x are Δx’: x₂ is the robust optimal solution
```
Steady-state database construction

- Test matrix is built by design of experiment (DoE) associating varied disturbances on all inputs in each test line (case)
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- Steady-state results are extracted from transient step response tests by an averaging window at the end of the cycle

### Inputs vs. Outputs

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>EGR</td>
<td>NOx</td>
</tr>
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<td>Inj pressure</td>
<td>NOx</td>
</tr>
<tr>
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Inputs

- EGR
- Inj pressure
- Inj ang
- Air flow
- Exh pressure

Outputs

- NOx

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Results @ operating point

Variation of NOx versus EGR around the operating point, **while all other parameters are held constant**

![Graph showing the variation of NOx versus EGR around the operating point.](image-url)
Results @ operating point

- Define NOx Engineering Target (ET) on this operating point and tolerances around ET.

Variation of NOx versus EGR around the operating point, while all other parameters are held constant.
Results @ operating point

- Define NOx Engineering Target (ET) on this operating point and tolerances around ET (PL)

- Make projection on parameter value (here EGR) to evaluate regulation constraints on inputs

Variation of NOx versus EGR around the operating point, while all other parameters are held constant
Results @ operating point

Flw air

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Results @ operating point

The scale of each input is reported in the legend.
Results @ operating point

- SOI
- Inj ang
- Inj pressure
- Flw air

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Results @ operating point

Inj ang
Inj pressure
Flw air
EGR
Results @ operating point

- SOI
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- EGR
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In this case, NOx is less robust against disturbances in air path than it is against disturbances in injection system.
2-Dimensionnal Results @ operating point
NOx is not all, other outputs have different sensitivity
Results @ operating point

AFR

- Inj ang
- Inj pressure
- Flw air
- EGR
- Exh pressure
More than 1D or 2D Sensitivity?

- Previous sensitivity curves allow to sort individual inputs by their disturbance gravity
- They show the amount of output variation as a response to the variation of one input (or two)
- They quantify the delta on output (or the worst case); the output will be somewhere in this interval; but:
  - The curves do not show the impact of multiple input variations (or cross variations)
  - The curves do not give an indication on the incidence rate (probability) of each level in this interval
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Probability Density Function

- Only min/max values are available about inputs disturbances
- A normal (Gaussian) distribution is considered with:
  - Mean value $\mu = \text{mean}(\text{min}, \text{max})$
  - Standard Deviation $\sigma = (\text{max}-\text{min})/6$
Probability Density Function

- Probability density function of the output (here NOx) is estimated by sampling in the input space and computing the output of each sample using the models.

Inputs

Probability Density Function of NOx

NOx

Probability

Cumulative Distribution Function

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- The cumulative distribution is the integral of the probability density function.
Example:
Cumulative Distribution Function

Example:
Example:

Only 80% of the products will be conform
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Probability Density Function of NOx

Cumulative Distribution Function of NOx
Comparison of two solutions

- The difference between the two solutions might be hard or soft (in this example the difference is only soft)

- Under the same disturbance, both datasets 1 and 2 reach the desired target (here 2 g/kWh NOx) on 55% of the cases (engine family)
Comparison of two solutions

- Under the same disturbance, if a margin is considered around the engineering target:
  - With dataset 2: conform engines top 93% of the cases
  - With dataset 1: conform engines dose not exceed 70% of the cases
Conclusion

• The analysis allows to assess the sensitivity of key outputs against different disturbing inputs/factors

• As a consequence, the tool directly helps to define/refine engine system requirement (system engineering approach)

• The analysis can help selecting more robust solutions (by simple change in dataset, or by soft/hard adaptation)