Introduction to LS-OPT

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Overview

- Introduction/Features
- Methodologies – Optimization
- Methodologies - Robustness
- Examples - Optimization
- Examples - Robustness
- Version 3.3 / Outlook
Introduction to LS-OPT – 14.05.08

- **About LS-OPT**
  - LS-OPT is a product of LSTC (Livermore Software Technology Corporation)
  - LS-OPT can be linked to any simulation code – stand alone optimization software
  - Methodologies/Features:
    - *Successive Response Surface Method (SRSM)*
    - *Genetic Algorithm (MOGA->NSGA-II)*
    - *Multidisciplinary optimization (MDO)*
    - *Multi-Objective optimization (Pareto)*
    - numerical/analytical based sensitivities
    - *Analysis of Variance (ANOVA)*
    - *Stochastic/Probabilistic Analysis*
    - *Monte Carlo Analysis using Metamodels*
    - ….
Introduction / Features

About LS-OPT

- Mixed Discrete-Continuous Optimization
  - Specify sets of discrete variables (e.g. sheet thicknesses)
- Robust Parameter Design (RDO)
  - Improve/Maximizing the robustness of the optimum
- Reliability Based Design Optimization (RBDO)
  - Improve failure probability of optimum
- Visualization of Stochastic Results
  - Confidence Intervals, reliability quantities
  - Fringe of statistic results on the FE-Model
About LS-OPT

- Job Distribution - Interface to Queuing Systems
  - PBS, LSF, LoadLeveler, SLURM, AQS, etc.
  - Retry of failed queuing (abnormal termination)
- LS-OPT might be used as a “Process Manager”
- Shape Optimization
  - Interface to ANSA, HyperMorph, DEP-Morpher, SFE-Concept
  - User-defined interface to any Pre-Processor
Introduction / Features

About LS-OPT

- LS-DYNA Integration
  - Checking of Dyna keyword files (*DATABASE_)
  - Importation of design parameters from Dyna keyword files (*PARAMETER_)
  - Monitoring of LS-DYNA progress
  - Result extraction of most LS-DYNA response types
  - D3plot compression (node and part selection)
About LS-OPT

- Parameter Identification Module
  - Handles "continuous" test curves
  - Automated use of test results to calibrate materials/systems
  - Simplify input for system identification applications
  - Visualization of test and simulation curve to compare
  - Confidence intervals for individual parameters in parameter identification

\[
\frac{1}{P} \sum_{i=1}^{P} W_i \left( \frac{F_i(x) - G_i}{\sigma_i} \right)^2
\]
Response Surface Methodology - Optimization Process

- Objective
- Design Variable 1
- Design Variable 2
- Design space
- Experimental Design points
- Response surface
- Starting (base) design
- Response values
- Subregion (Range)
Find an Optimum on the Response Surface (one iteration)

- Optimization of sub-problem (response surface) using LFOPC algorithm
- Optimum (predicted by response surface)
- Optimum (computed by simulation using design variables)
- Starting value on response surface
Successive Response Surface Methodology

Design Variable 1

Design Variable 2

Design Space

Region of Interest

starting design

optimum

1 2 3 4 5 6 7 8

Introduction to LS-OPT – 14.05.08
Successive Response Surface Methodology

Example - 4th order polynomial

\[ g(x) = 4 + \frac{9}{2}x_1 - 4x_2 + x_1^2 + 2x_2^2 - 2x_1x_2 + x_1^4 - 2x_1^2x_2 \]
**Design of Experiments (DOE) - Sampling Point Selection**

- Koshal, Central Composite, Full Factorial
- **D-Optimality Criterion** - Gives maximal confidence in the model

\[
\max \left| X^T X \right|
\]

- Monte Carlo Sampling
- Latin Hypercube Sampling (stratified Monte Carlo)
- Space Filling Designs
- User Defined Experiments
Response Surfaces (Meta Models)
- Linear, Quadratic and Mixed polynomial based
- Neural Network and Kriging for Nonlinear Regression

linear polynomial

quadratic polynomial

neural network
Neural Network Regression

Example - 4th order polynomial

\[
g(x) = 4 + \frac{9}{2} x_1 - 4x_2 + x_1^2 + 2x_2^2 - 2x_1x_2 + x_1^4 - 2x_1^2x_2
\]
Meta-Model Viewer - Exploration of Design Space

Compare responses, histories or even different optimization projects.
About D-SPEX

- **D-SPEX – Design SPace EXplorer**
- D-SPEX is a software tool for the visualization of Meta-Models and results of optimization or stochastic analysis
- Versions Windows 32/64bit and Linux 32/64bit
- Complete interface to LS-OPT database
- Developed by DYNAmore in collaboration with AUDI (property of DYNAmore)
- Methodologies/Features:
  - *Meta-Model viewer*
  - *Curve statistics*
  - *Feasible/Infeasible design*
  - *Ant-Hill plots*
  - *Statistic evaluations*
## Overview – Optimization Methodologies for highly nonlinear Applications

<table>
<thead>
<tr>
<th>Gradient Based Methods</th>
<th>Random Search</th>
<th>Genetic Algorithms</th>
<th>RSM / SRSM</th>
</tr>
</thead>
</table>
| $\bullet$ accuracy of solution  
$\bullet$ number of solver calls |
| $\bullet$ very robust, can not diverge  
$\bullet$ easy to apply |
| $\bullet$ good for problems with many local minimas |
| $\bullet$ very effective, particularly SRSM  
$\bullet$ trade-off studies on RS  
$\bullet$ filter out noise, smoothing of results |
| $\bullet$ can diverge  
$\bullet$ can stuck in local minimas  
$\bullet$ step-size dilemma for numerical gradients |
| $\bullet$ bad convergence, not effective  
$\bullet$ Chooses best observation – may not be representative of a good (robust) design |
| $\bullet$ many solver calls, only suitable for fast solver runs  
$\bullet$ Chooses best observation – may not be representative of a good (robust) design |
| $\bullet$ approximation error  
$\bullet$ verification run might be infeasible  
$\bullet$ number of variables control minimum number of required runs |
Stochastic Analysis - Goals

- Statistical Quantities of Output (Response) due to Variation of Input (Parameter)
  - Mean
  - Standard deviation
  - Distribution function

- Significance of Parameter with respect to Responses
  - Correlation analysis
  - Stochastic contributions
  - ANOVA – analysis of variance

- Reliability Issues
  - Probability of failure

- Visualization of statistical quantities on FE-model
  - Spatial detection of variation/correlation
Statistical Quantities of Output due to Variation of Input

- Direct Monte Carlo Sampling
  - *Latin Hypercube sampling*
  - *Large number of FE runs (100+)*
  - *Consideration of confidence intervals for mean, std. dev., correlation coeff.*
Statistical Quantities of Output due to Variation of Input

- Monte Carlo using Meta-Models
  - Response Surface / Neural Network
  - Medium number of FE runs (10 – 30+)
  - Number of runs depend on the dimension of the problem (number of variables) and the type of the response surface
- Identify design variable contributions clearly
- Exploration of parameter space -> D-SPEX
### Stochastic Analysis - Goals

- Statistical Quantities of Output (Response) due to Variation of Input (Parameter)
  - mean
  - standard deviation
  - distribution function

- Significance of Parameter with respect to Responses
  - correlation analysis
  - stochastic contributions
  - ANOVA – analysis of variance

- Reliability Issues
  - Probability of failure

- Visualization of statistical quantities on FE-model
  - Spatial detection of variation/correlation
Significance of Variables

- Correlation Analysis
- ANOVA - Meta-Model based
- Stochastic Contributions – Meta-Model based

Correlation Matrix

<table>
<thead>
<tr>
<th></th>
<th>input</th>
<th></th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.02</td>
<td>-0.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-0.17</td>
<td>0.06</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>-0.01</td>
<td>0.32</td>
<td>-0.26</td>
<td>-0.28</td>
</tr>
<tr>
<td>0.02</td>
<td>0.08</td>
<td>-0.14</td>
<td>0</td>
</tr>
<tr>
<td>0.06</td>
<td>-0.03</td>
<td>-0.85</td>
<td>-0.53</td>
</tr>
<tr>
<td>0.16</td>
<td>0.18</td>
<td>0.68</td>
<td>0.22</td>
</tr>
</tbody>
</table>

important variables

ANOVA
Stochastic Analysis - Goals

- Statistical Quantities of Output (Response) due to Variation of Input (Parameter)
  - mean
  - standard deviation
  - distribution function
- Significance of Parameter with respect to Responses
  - correlation analysis
  - stochastic contributions
  - ANOVA – analysis of variance
- Reliability Issues
  - Probability of failure
- Visualization of statistical quantities on FE-model
  - Spatial detection of variation/correlation
Reliability Analysis

- Probability of failure
- Evaluation of confidence interval
- Prediction error (confidence interval) depends on the number of runs
- on the probability of event
- not on the dimension of the problem (number of design variables)

Probability of 8.4% for violating the FORCE-bound
Stochastic Analysis - Goals

- Statistical Quantities of Output (Response) due to Variation of Input (Parameter)
  - mean
  - standard deviation
  - distribution function

- Significance of Parameter with respect to Responses
  - correlation analysis
  - stochastic contributions
  - ANOVA – analysis of variance

- Reliability Issues
  - Probability of failure

- Visualization of statistical quantities on FE-model
  - Spatial detection of variation/correlation
Visualization of Statistical Quantities on FE-model

- Standard deviation of y-displacements of each node (40 runs)

RUN 1
Buckling mode A

RUN 8
Buckling mode B

High Variance of y-displacement

Courtesy DaimlerChrysler
Example I - Optimization

Optimization of an Adaptive Restraint System

Four Different Front-Crash Load Cases (FMVSS 208)

<table>
<thead>
<tr>
<th>Dummy</th>
<th>56 km/h – belted</th>
<th>40 km/h – not belted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid III 5th Female</td>
<td>H305a(ktiv)</td>
<td>H305p(assiv)</td>
</tr>
<tr>
<td>Hybrid III 50th Male</td>
<td>H350a(ktiv)</td>
<td>H350p(assiv)</td>
</tr>
</tbody>
</table>

PAM-Crash Model

- about 500000 elements
- wall clock simulation time ~19 h, 4 cpus, distributed memory

Load Case Detection available

- Differentiation of the loadcases belted / not belted and “Hybrid III 5th Female“ / „Hybrid III 50th Male“ possible
- Trigger time for seatbelt, airbag and steering column might be different
### Design Variables

#### Adaptive Airbag Deployment (6 Variables)

<table>
<thead>
<tr>
<th></th>
<th>H305a 5%-dummy, belted</th>
<th>H305p 5%-dummy, not belted</th>
<th>H350a 50%-dummy, belted</th>
<th>H350p 50%-dummy, not belted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area Venthole 1</td>
<td>FAB_VENT</td>
<td>FAB_VENT</td>
<td>FAB_VENT</td>
<td>FAB_VENT</td>
</tr>
<tr>
<td>Lower – Upper B.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area Venthole 2</td>
<td>SBA_VENT</td>
<td>SBA_VENT</td>
<td>SBA_VENT</td>
<td>SBA_VENT</td>
</tr>
<tr>
<td>Lower – Upper B.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trigger Time</td>
<td>FAB_ADT1_05a</td>
<td>FAB_ADT1_05p</td>
<td>FAB_ADT1_50a</td>
<td>FAB_ADT1_50p</td>
</tr>
<tr>
<td>Lower – Upper B.</td>
<td></td>
<td></td>
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![Diagram of adaptive airbag deployment](image-url)
Design Variables

Adaptive Steering Column (5 Variables)

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<thead>
<tr>
<th></th>
<th>H305a</th>
<th>H305p</th>
<th>H350a</th>
<th>H350p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5%-dummy, belted</td>
<td>5%-dummy, not belted</td>
<td>50%-dummy, belted</td>
<td>50%-dummy, not belted</td>
</tr>
<tr>
<td>Force Level StCo</td>
<td>LKS_SKAL</td>
<td>LKS_SKAL</td>
<td>LKS_SKAL</td>
<td>LKS_SKAL</td>
</tr>
<tr>
<td>Lower – Upper Bound</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trigger Time</td>
<td>LKS_DOWN05a</td>
<td>LKS_DOWN50a</td>
<td>LKS_DOWN05p</td>
<td>LKS_DOWN50p</td>
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<td>Lower – Upper Bound</td>
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Introduction to LS-OPT – 14.05.08
### Design Variables

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<td>LKS_SKAL</td>
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<tr>
<td>Lower – Upper Bound</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trigger Time</td>
<td>LKS_DOWN05a</td>
<td>LKS_DOWN50a</td>
<td>LKS_DOWN05p</td>
<td>LKS_DOWN50p</td>
</tr>
<tr>
<td>Lower – Upper Bound</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Diagram:**
- Force Steer. Colu.
- LKS_SKAL
- Time [t]
Optimization Problem

Objective

Minimize Thorax Acceleration

- \( \text{min BrustA3ms-05a} \)
- \( \text{min BrustA3ms-50a} \)
- \( \text{min BrustA3ms-05p} \)
- \( \text{min BrustA3ms-50p} \)

Constraints < 80% of regulation requirements

- Head Injury Coefficient (15ms)
  - \( \text{HIC15-05a} \)
  - \( \text{HIC15-50a} \)
  - \( \text{HIC15-05p} \)
  - \( \text{HIC15-50p} \)

- Femur Forces (left/right)
  - \( \text{FemurLi-05a} \)
  - \( \text{FemurLi-50a} \)
  - \( \text{FemurLi-05p} \)
  - \( \text{FemurLi-50p} \)

- Thorax Intrusion
  - \( \text{BrustSx-05a} \)
  - \( \text{BrustSx-50a} \)
  - \( \text{BrustSx-05p} \)
  - \( \text{BrustSx-50p} \)

- Thorax Acceleration
  - \( \text{BrustA3ms-05a} \)
  - \( \text{BrustA3ms-50a} \)
  - \( \text{BrustA3ms-05p} \)
  - \( \text{BrustA3ms-50p} \)
Example I - Optimization

Process Work Flow

Input Files
- H305a.pc
- H305p.pc
- H350a.pc
- H350p.pc

Variables
- GUR_ENDE05a
- FABADT1_05a
- LKS_DOWN05a
- FABADT1_05p
- LKS_DOWN05p
- LKS_SKAL
- FAB_VENT
- SBA_VENT
- GUR_FOR1
- FABADT1_50a
- LKS_DOWN50a
- GUR_ENDE50a
- FABADT1_50p
- LKS_DOWN50p
- FABADT1_50p
- LKS_DOWN50p

PAM-CRASH

LSF

EVALUATOR

Local
- Femur-05a
- Femur-05p
- Femur-50a
- Femur-50p

Remote
- HIC15-05a
- HIC15-05p
- HIC15-50a
- HIC15-50p
- ThoraxSx-05a
- ThoraxSx-05p
- ThoraxSx-50a
- ThoraxSx-50p
- Thoraxa3ms-05a
- Thoraxa3ms-05p
- Thoraxa3ms-50a
- Thoraxa3ms-50p
Application of Optimization

Preferred Configuration at AUDI
- Adaptive Restraint System only for Airbag and Seatbelt
- Reduction to 9 Variables in total (active=6, passive=3)

LS-OPT Approach: Successive Response Surface Methodology (SRSM) using linear polynomial approximations
- 34 runs per iteration
- D-optimal Design of Experiments (DOE)

Results
- 8 iterations - total runs: 276
- all constraints are fulfilled
- minimization of multi-objective (second step) not applied
Example I - Optimization

Optimization Progress

a result which meets all requirements is gained in 8 iterations, each with 34 shots
Parameter Identification of Plastic Material

- Material properties: nonlinear visco-elastic behaviour
- LS-DYNA hyperelastic/viscoelastic formulation - *MAT_OGDEN_RUBBER (#77)

Hyperelasticity

\[ W = \sum_{i=1}^{3} \sum_{j=1}^{n} \frac{\mu_j}{\alpha_j} (\lambda_i^{\alpha_j} - 1) + \frac{1}{2} K (J - 1)^2 \]

Prony series representing the visco-elastic part (Maxwell elements):

\[ g(t) = \sum_{m=1}^{N} G_m e^{-\beta_m t} \quad ; \quad N=1, 2, 3, 4, 5, 6 \quad ; \quad \sigma_{ij} = \int_{0}^{t} g_{ijkl} (t - \tau) \frac{\partial e_{kl}}{\partial \tau} d\tau \]
**Example I - Optimization**

Parameter Identification of Plastic Material

- Minimize the distance between experimental curve and simulation curve
- Least-Squares Objective Function

\[
F(x) = \sum_{p=1}^{P} \{ [y(x) - f(x)]^2 \} \rightarrow \min F(x)
\]

Strain rate \( A \) $\rightarrow$ fit of Prony terms

quasi-static curve $\rightarrow$ Ogden fit
Example III – Optimization

Shape Optimization of a Crash Box

- Scope of optimization:
  - minimize the maximum crash force
  - steady-going force progression

- Shape variation by using Hypermorph and LS-OPT (20 design variables)
Example I – Robustness

Robustness Investigations – Monte Carlo Analysis

Variation of sheet thicknesses and yield stress of significant parts in order to consider uncertainties.

Normal distribution is assumed:

- \( T_{1134} \) (Longitudinal Member)  \[ \text{mean} = 2.5\, \text{mm}; \quad \sigma = 0.05\, \text{mm} \]
- \( T_{1139} \) (Closing Panel)  \[ \text{mean} = 2.4\, \text{mm}; \quad \sigma = 0.05\, \text{mm} \]
- \( T_{1210} \) (Absorbing Box)  \[ \text{mean} = 0.8\, \text{mm}; \quad \sigma = 0.05\, \text{mm} \]
- \( T_{1221} \) (Absorbing Box)  \[ \text{mean} = 1.0\, \text{mm}; \quad \sigma = 0.05\, \text{mm} \]
- \( SF_{1134} \) (Longitudinal Member)  \[ \text{mean} = 1.0 \quad \sigma = 0.05 \]

Monte Carlo analysis using 182 points (Latin Hypercube)
Example I – Robustness

 situación

 Tradeoff Plot

 Monte Carlo Simulation

 Identification of Clustering
Example I – Robustness

Reliability Analysis
- Histogram of distribution
- Probability of exceeding a constraint-bound

Min-Max Curves
- Plot of minimum, maximum and mean history values
- Gives a confidence interval of history values

Probability of 8.4% for violating the RWFORC-bound

Min-Max Curves
- Plot of minimum, maximum and mean history values
- Gives a confidence interval of history values
Example II – Robustness

Design Variables - Uncertainties in Test Set-Up

- Slip Ring Friction: sfric1
- Pre-Tensioner: preten
- Force Limit Retractor: forcelimit
- Airbag Mass Flow: scal_massflow
- Steering Wheel: rot_stwh
- Sled Acceleration: scalaccel
- Slip Ring Friction: sfric2
- Dashboard: young_alu x_transl z_transl
### Stochastic Contribution - Results of 30 Experiments

<table>
<thead>
<tr>
<th>Design Variable</th>
<th>Standard Deviation of Design Variable</th>
<th>Standard Deviation Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HIC6</td>
<td>max_chest</td>
</tr>
<tr>
<td>scalaccel</td>
<td>2,5%</td>
<td>3,1%</td>
</tr>
<tr>
<td>sfric1</td>
<td>25,0%</td>
<td>1,3%</td>
</tr>
<tr>
<td>sfric2</td>
<td>25,0%</td>
<td>0,5%</td>
</tr>
<tr>
<td>preten</td>
<td>4,4%</td>
<td>0,0%</td>
</tr>
<tr>
<td>forcelimit</td>
<td>5,6%</td>
<td>1,3%</td>
</tr>
<tr>
<td>rot_stwh</td>
<td>4,8%</td>
<td>0,5%</td>
</tr>
<tr>
<td>transl_x</td>
<td>50,0%</td>
<td>0,1%</td>
</tr>
<tr>
<td>transl_z</td>
<td>50,0%</td>
<td>1,2%</td>
</tr>
<tr>
<td>scalmassflow</td>
<td>5,0%</td>
<td>1,8%</td>
</tr>
<tr>
<td>young_alu</td>
<td>5,0%</td>
<td>0,3%</td>
</tr>
<tr>
<td>all variables</td>
<td></td>
<td>4,3%</td>
</tr>
<tr>
<td>residuals</td>
<td></td>
<td>4,7%</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>6,4%</td>
</tr>
</tbody>
</table>
Example II – Robustness

- Standard deviation of x-displacements of each node (120 runs)

(a) Deterministic (Meta-Model)

(b) Residual (Outliers)
Version 3.3

- Improvements of Meta-Models
  - Implementation of Radial Basis Functions
  - Speed/Performance enhancements of Neural Networks
- Genetic Algorithm (MOGA – NSGA-II)
  - Improve of Multi-Objective Optimization (Pareto Fronts)
  - Direct GA available
- Tied ANSA Interface
  - User friendly coupling of ANSA
- Extra Input Files
  - Additional Input Files containing Variables can be specified
  - For other solvers than LS-DYNA
Version 3.3

- DYNAsstats for Metal Forming
  - Available for adaptive meshing
  - Mapping of nodal/element results onto reference mesh
- 3-D metamodel plot enhancements
  - Activate Post-Processor on point selection
  - Add value list display on point selection (similar to 2D)
- ANOVA chart enhancements
  - Positive/negative correlation
- DOE-Task for Sensitivities and Variable Screening
  - Dedicated task for DOE-Study (no optimization)
Version 3.3

- Interface for User-defined Meta Models
- Summary Report File
- Import of Check Points
  - Calculation of predicted values for user-defined points
Outlook

- Generic File extractor
  - *Extraction of values from any ASCII input file*
- Visualization of “Pareto Fronts” for Multi-Objective Optimization (MOO)
  - *Difficult for more than 3 objectives*
- *Correlated Input Variables for Stochastic Investigations*
- Additional injury criteria (DYNA extraction)
  - *IIHS, neck/tibia indices,…*
Thanks for your attention!