Multivariate GT-Power Analysis

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Introduction

• Multivariate Technology
  – The study of functions involving more than one variable
  – Design of Experiments (DOE)
  – Response surface modelling
  – Multivariate data analysis

• Synergy with GT-Power simulation
  – Optimisation of gas exchange variables
  – Robustness testing
  – Estimation of unknown input data at the design stage

• Computer packages used by CT
  – Umetrics
    ß User friendly and simple
  – Matlab calibration toolbox
    ß Highly advanced functionality
Design of Experiments (1)

COST Sweep 1

COST Optimum
(Changing One Separate factor at a Time)

COST Optimum

Response Surface

Variable 2

Variable 1

Integrated Powertrain Solutions
Design of Experiments (2)

- Conventional optimisation / characterisation of responses
  - Changing one separate factor at a time (COST)
  - Doesn’t identify the correct optimum
    - Different location depending on starting point
  - No quantification of interactions
- Full factorial
  - Calculate all points in a grid
  - Shows correct optimum and interaction between variables
  - Large number of points
    - Especially with a large number of variables
    - No Points = Levels to the power of the number of factors, \( L^f \)
- Aim of design of experiments
  - Identify the minimum number of points to characterise the design space
  - Evaluate all variables together
    - Identify correct optimum
    - Quantify interactions
• Umetrics Modde DOE software
  – Gives DOE capability to the non-specialist
    - User friendly
    - Application based training
  – Inexpensive
    - Site wide license
  – Mainly limited to simple, classical experiments
  – Quadratic surface fits only
  – Some non-standard features
    - D-Optimal designs
      - Irregular domains
    - Qualitative factors
    - Alternative regression methods
      - Multiple linear regression
      - Partial least square
Umetrics Modde Example 1 (DOE)

- Valve event optimisation
- Four factors
- One response of IMEP
- Central composite face-centred design (CCF)

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# Umetrics Modde Example 1 (Results)

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INDUR, EXDUR, IMOP and EMOP set up in GT-Power as parameters.

Response IMEP predicted and copied into Modde.
IMEP = k1 + k2.INDUR + k3.EXDUR + k4.IMOP + k5.EMOP + k6.IMOP^2 + k7.EMOP^2 + k8.INDUR^2 + k9.EXDUR^2 + k10.INDUR.EXDUR + k11.INDUR.IMOP + k11.INDUR.EMOP + k12.EXDUR.IMOP + k13.EXDUR.EMOP + k14.IMOP.EMOP

Investigation: Valve_Event_DOE_2nd_Stage (MLR)
Scaled & Centered Coefficients for IMEP

N=25  R2=0.986  R2 Adj.=0.972
DF=12  Q2=0.936  RSD=1.7072  Conf. lev.=0.95
Umetrics Modde Example 1 ($R^2$ and $Q^2$)

Investigation: Valve_Event_DOE_2nd_Stage (MLR)
Summary of Fit

$R^2 = \text{Measure of fit, } Q^2 = \text{Measure of predictive ability}$
Umetrics Modde Example 1 (Fit vs Observed)

Investigation: Valve_Event_DOE_2nd_Stage (MLR)
IMEP

Observed vs Predicted chart showing the relationship between observed and predicted values for IMEP.
Umetrics Modde Example 1 (Comparison)

**DOE Contour**
Run time: 20min

**Full Factorial for inlet and exhaust duration**
GT-Power optimiser for IMOP and EMOP
Run time: 870min
• Volumetric efficiency targets were set at 6000, 4800 and 3600rpm
• Parameters available for tuning were:
  – Primary length
  – Runner inlet diameter
  – Plenum volume
• A three factor DOE was set up and run at each speed
  – IMOP optimised independently at each point
    ß GT-Power’s optimiser
• The maps of volumetric efficiency were studied to identify the best compromise solution
• All DOE’s gave good statistics – $R^2$, $Q^2$ 95%+
• All DOE’s tested with sweeps through each range, varying length at constant diameter etc.
• 6000rpm DOE showed discrepancy with sweep
• Map of length and diameter at fixed plenum vol run to check
Inlet runner length vs. Inlet runner diameter

6000rpm
Umetrics Modde Example 2 (Modified Range)

- DOE specifies points at min, max and centre for each of the ranges, fits quadratic contour to these ranges.
- For 6000rpm, the trends are not accurately represented by a quadratic fit.
- DOE stats report very good fit, but only to the points it knows about.
- Not a problem for low speed results as original ranges correctly characterised the response.

- Model rerun for 6000rpm over limited length.
- Trend is now quadratic and therefore successfully fitted by Modde.
Umetrics Modde Example 2 (Results)

- Small plenum vol
- Med plenum vol
- Large plenum vol

6000rpm

4800rpm

3600rpm

Inlet Diameter

Primary Length

Shaded areas fail to meet performance
Matlab Model Based Calibration Toolbox

• MBC Toolbox
  – Highly advance functionality
    ß DOE options
      - Space-filling, D-optimal and classical strategies
    ß Response surface modelling
      - Polynomials, cubic spline, radial basis functions
    ß One or two-stage models
  – Expensive compared to Modde
  – Requires greater user capability to understand additional model complexity
• Three factor design
  – Exhaust primary length
  – Exhaust primary diameter
  – Cylinder bore
• Space filling design
  – Useful when there is little idea of the response shape
  – Spreads the points evenly throughout operating space
    ß Based on a set of rules for achieving regular spacing
    - Stratified Latin Hypercube
• Design evaluation
  – Predicted error variance <1
Matlab Example (Results)

GT-Power map

Matlab cubic spline surface fit
Two Stage Modelling

- Two stage modelling
  - Local DOE around each point of the global DOE
  - Cam timing optimisation
    - Local DOE:
      - IMOP, EMOP
    - Example Global DOE:
      - Exh primary and secondary lengths
  - Taguchi Robustness testing
    - Low variability with operating point
    - Local DOE:
      - Exhaust wall temperature and back pressure
      - Different on test bed and in vehicle
Multivariate data analysis

- Allows trends to be extracted from collections of data
- Principal component analysis identifies the qualitative relationship between variables
- Partial least square regression allows linear surface contours to be predicted
- The application allows improved estimates for GT-Power inputs

Example: characterisation of test bed CAI combustion data
(Responses 50% BP and 10 to 90 Duration, factors inlet and exhaust cam position)
Summary

- Multivariate technology allows the effect of many variables on a response to be assessed simultaneously
- Classical DOE designs with quadratic surface fits can significantly speed up the optimisation process
  - Suitable for use by the non-specialist
  - Ranges must be carefully selected to ensure the trends do not become cubic
- Advanced DOE software and greater expertise is required for:
  - Multiple dips and valleys within the design space
    - Radial basis functions, cubic splines
  - Assessing design spaces where little or no information regarding the effects of factors on the responses
    - Space filling designs
- Two stage modelling is beneficial for cam timing optimisations and robustness testing
- Multivariate data analysis is beneficial for extrapolating GT-Power inputs from a collection of test data