Innovative Fusion of Experiment and Analysis for Missile Design and Flight Simulation

Patrick H. Reisenthel, John F. Love,
Daniel J. Lesieutre, and Marnix F. E. Dillenius
Nielsen Engineering & Research, Inc., Mountain View, CA 94043, USA

RTO Symposium on Innovative Missile Systems
15-18 May 2006, Amsterdam

NIELSEN ENGINEERING & RESEARCH, INC.

Introduction

- Integration of experimental and computational data
  - key to supporting decisions during the development of aerospace products
- Heterogeneous data sets
  - Mutually enhanced
  - Multidimensional response surface technology
- Application:
  - Use of sparse experimental data to correct a computational database for use in comprehensive flight simulations of missiles

Motivation

- Develop global understanding of the data
- Common situation…
- Data fusion technique via response surface methods
  - not conventional interpolation / data fitting
  - computational (model) based
- Dual aspects:
  - interpolation/extrapolation of limited experimental data
  - fine-tuning / calibration of computational models

Mutual Enhancement of Data Sets

- Data generalization
  - ill-posed problem
  - regularizing assumptions
    - physics based models
    - mathematical equations
    - smoothness assumptions
    - empiricism
    - **Hypersurface (NEAR RS)**
      - goes through the experimental data
      - "supported" by additional computational constraints

NIELSEN ENGINEERING & RESEARCH, INC.

N-Dimensional Response Surface Calculation

- Identify smooth mapping $F : \mathrm{R}^N \rightarrow \mathrm{R}$ $\quad F(\mathbf{X}_i) = Y_i, \quad i = 1, \dots, p$
- Minimize the distance $\| F(X_i) - Y_i \|$
- Expand F into radial basis functions

$$F(X) = \sum_k c_k \varphi_k(X), \quad \varphi_k(X) = f(\| X - \chi_k \| ; b)$$

f is a shape function

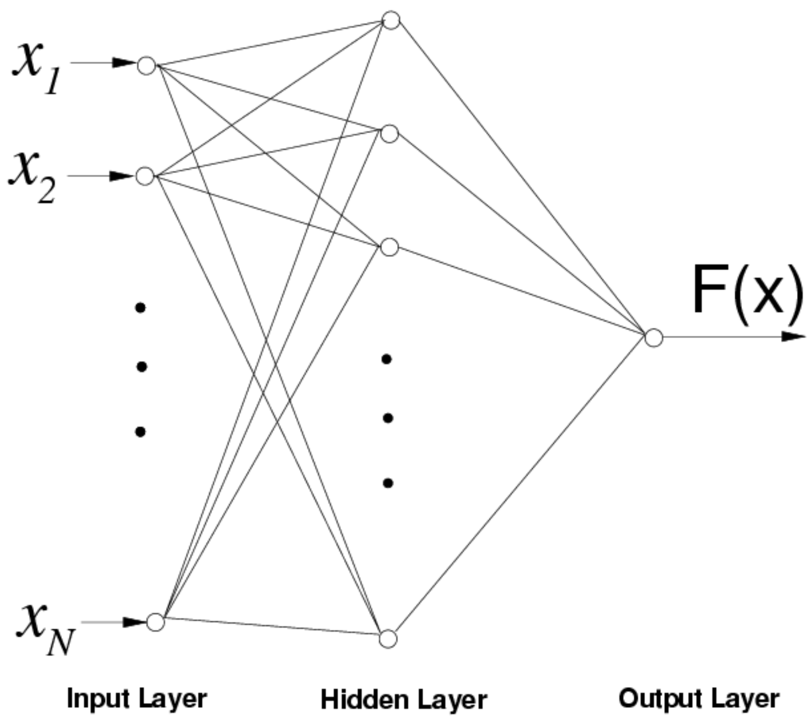
b is a scale or stiffness parameter

$(\chi_k ; F(\chi_k))$ RS support vectors

c_k solution of least-squares problem

NIELSEN ENGINEERING & RESEARCH, INC.

Radial Basis Function Network



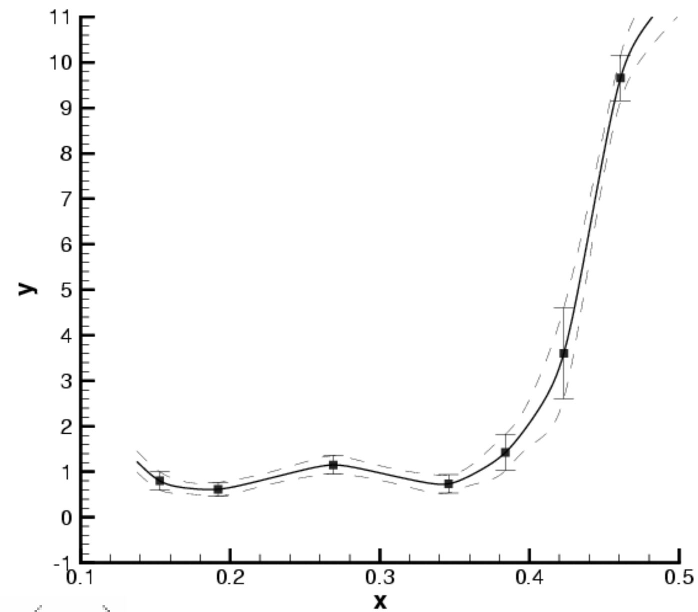
NIELSEN ENGINEERING & RESEARCH, INC.

Uncertainty Prediction (NEAR RS)

- If *f*, *b*, χ_k are known $\Rightarrow$ linear system [A][C] = [Y]
- Regressor model for the data: [A][C] = [Y] + [*e*]
- Since $F(X) = \sum_k c_k \varphi_k(X)$
- Propagate uncertainty:

$$\mathrm{var}(F) = \sum_i \sum_j \left(cov[C]\right)_{ij} \varphi_i(X) \varphi_j(X)$$

$\delta Y_i \rightarrow \delta c_k \rightarrow \delta F$



Application to Data Fusion

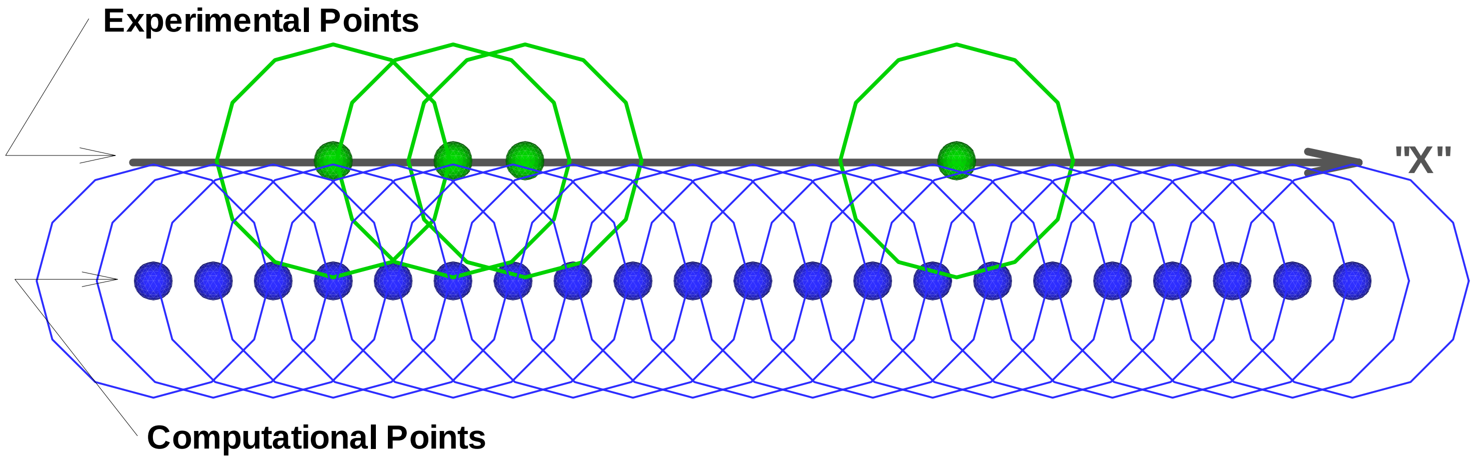
- "The combination of a group of inputs with the objective of producing a single output of greater quality and greater reliability." (Li et al., 1993)
- Two sources of data
  - computational (approximations in physical models)
  - experimental (limitations, cost, sparse)
  - not same sampling, conditions
- Construct global metamodel incorporating all the data

Method

- Introduce auxiliary variable $\varepsilon \equiv x_{N+1}$ added to the multidimensional space $(x_1, x_2, \ldots, x_N)$
- ε used to tag whether data are computational $\varepsilon = 0$ or experimental $\varepsilon = 1$
- Single response surface calculated in *N*+1 dimensions, queried in the $\varepsilon = 1$ subspace

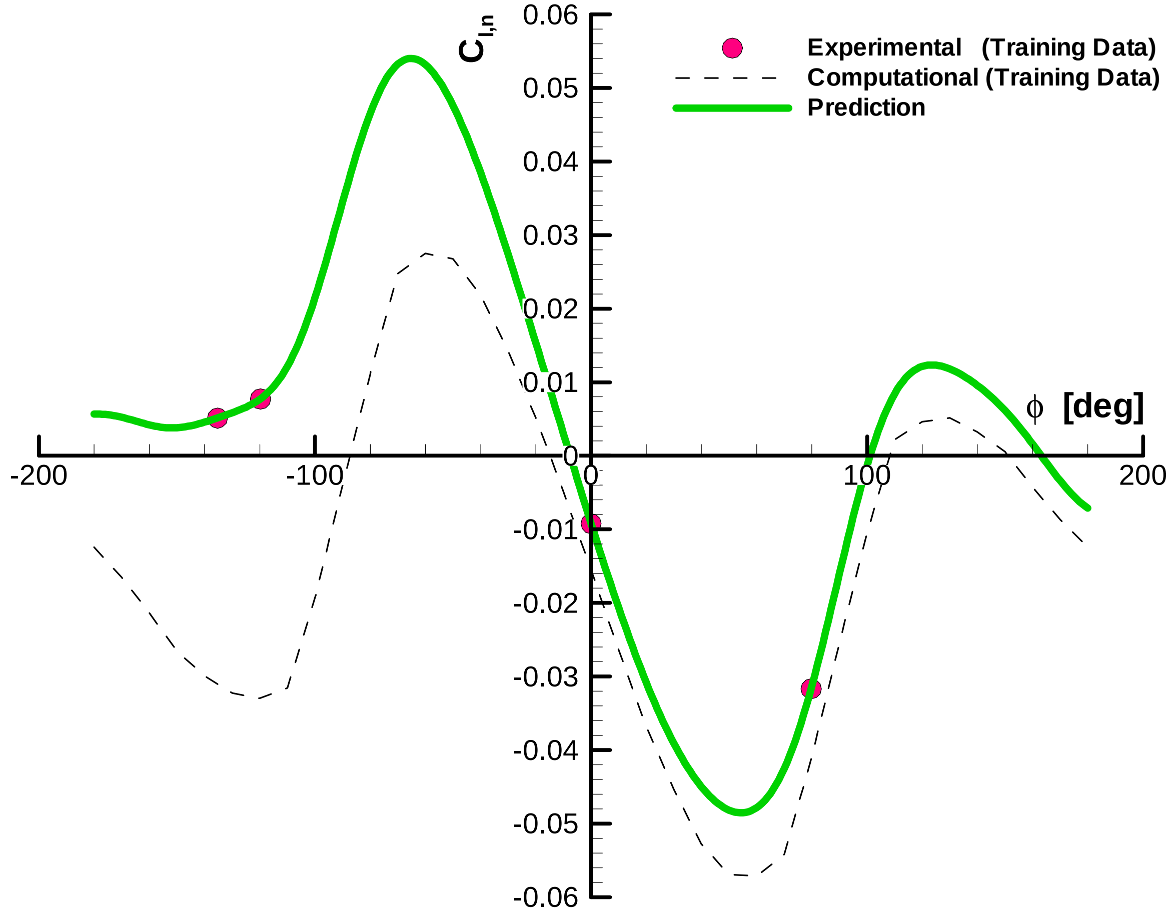
NIELSEN ENGINEERING & RESEARCH, INC.

Geometric Interpretation



NIELSEN ENGINEERING & RESEARCH, INC.

Fusion Example



NIELSEN ENGINEERING & RESEARCH, INC.

Fusion Example (Concluded)

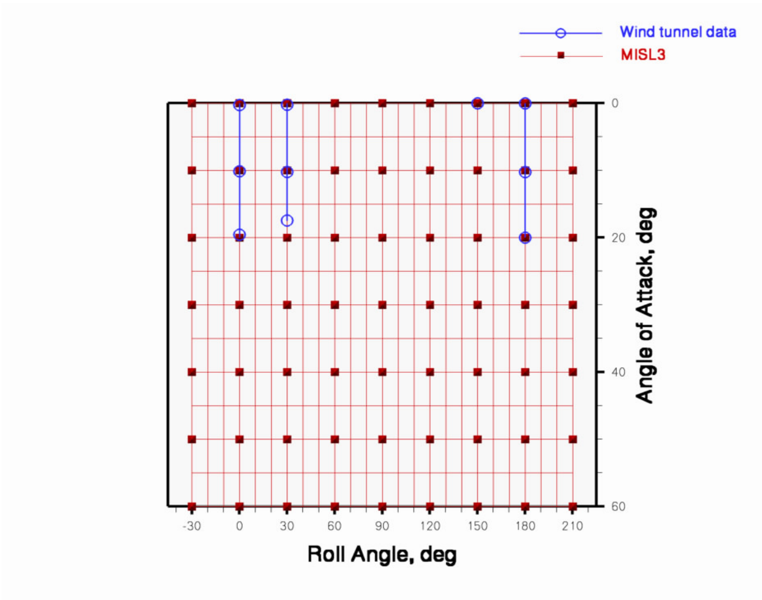
- Importance of using computational models which incorporate the correct physics
  - specially important when performing sparse data interpolation/extrapolation
- "Two experimental points" example is relevant to the case of multidimensional data
  - finite resources (time and budget) limit the number of conditions that can be acquired
  - modern design-of-experiment techniques can help, but
  - "filling in" the space remains an impossibility when the number of independent variables is large
  - sparse sampling in *some* directions to be expected

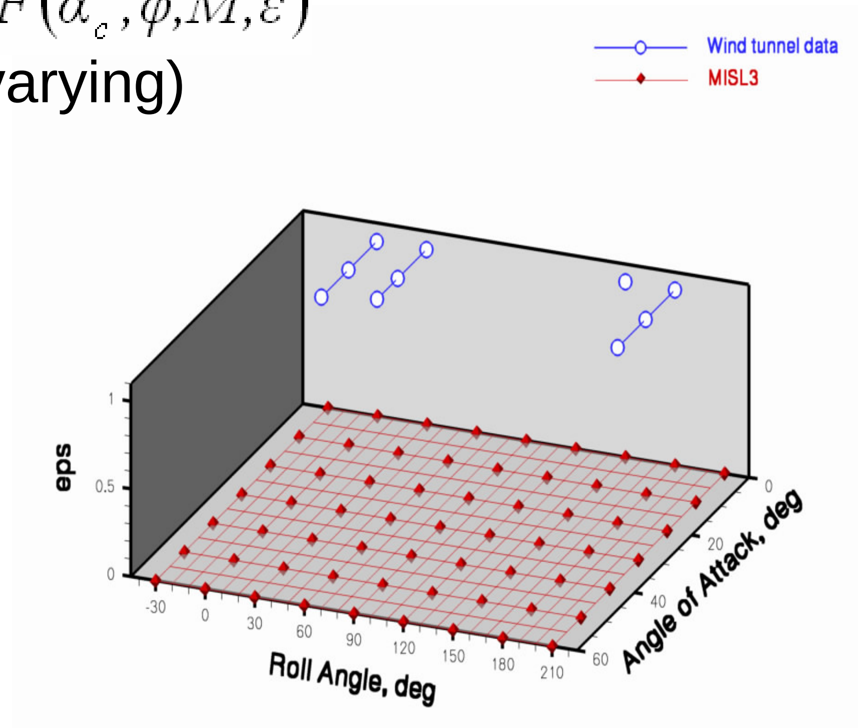
Correction of Aerodynamic Databases Using Experimental Data

- Assimilation of limited wind tunnel data
  - goal: increase the accuracy of comprehensive flight simulations of a missile
- Generic body-tail configuration
- Two data sets
  - sparse experimental (wind tunnel) data
  - "computational" database (MISL3)
    - Forces and moments
    - Wide range of angles of attack, roll angles, and Mach numbers
- "Error database"

Error database

- Defined as difference between two fits
  - Four-dimensional $F(\alpha_c, \varphi, M, \varepsilon)$
  - Analytic (smoothly varying)



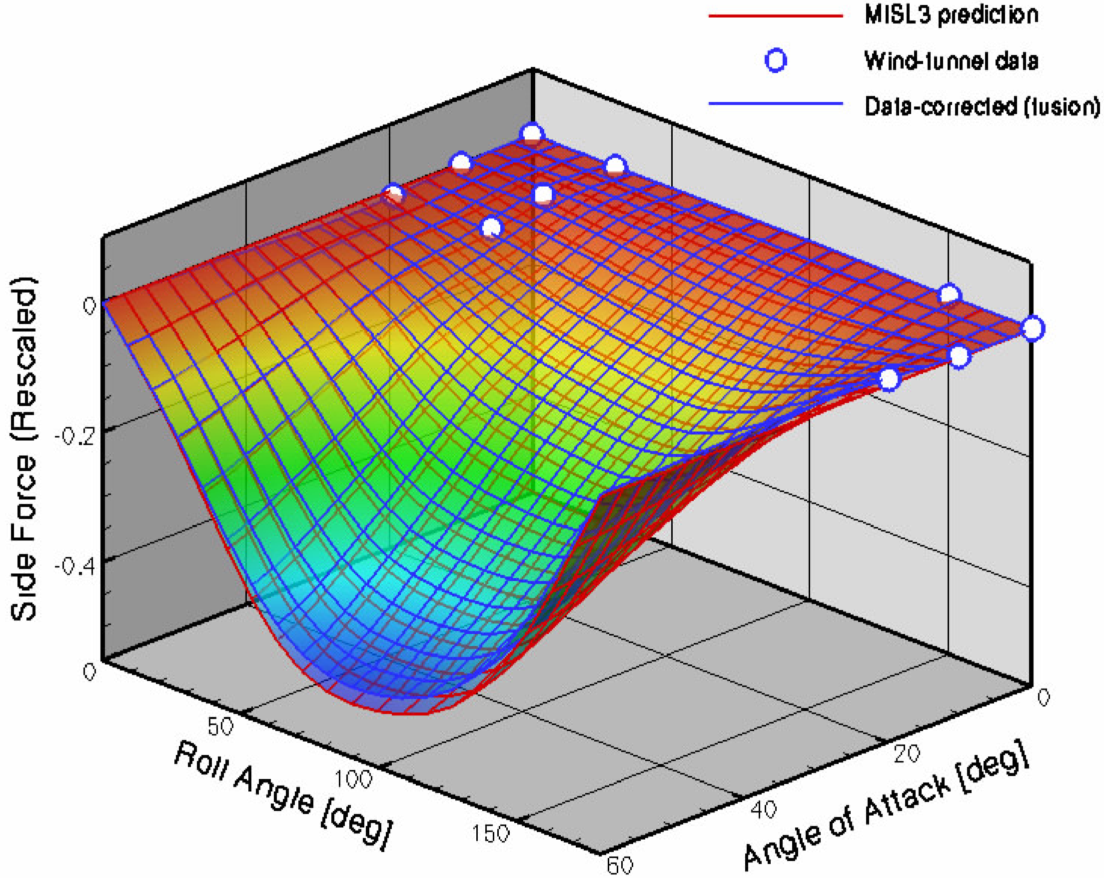


NIELSEN ENGINEERING & RESEARCH, INC.

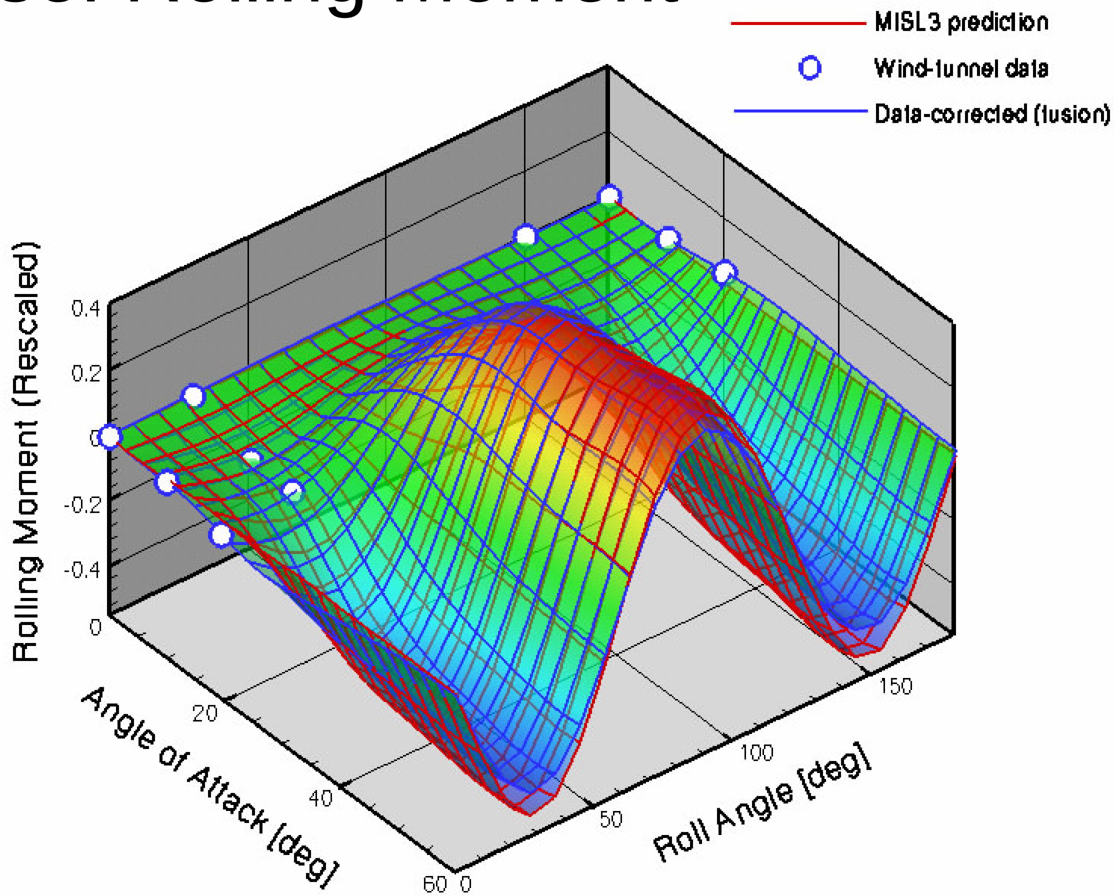
Error database (Cont'd)

- Used to "correct" MISL3 database
  - takes into account experimental measurements
- Smart interpolation/extrapolation
  - process is automatic
  - no equations specified
  - requires only the specification of support vectors

Wind Tunnel Data Enhancement of MISL3 Database: Side Force Results



Wind Tunnel Data Enhancement of MISL3 Database: Rolling Moment

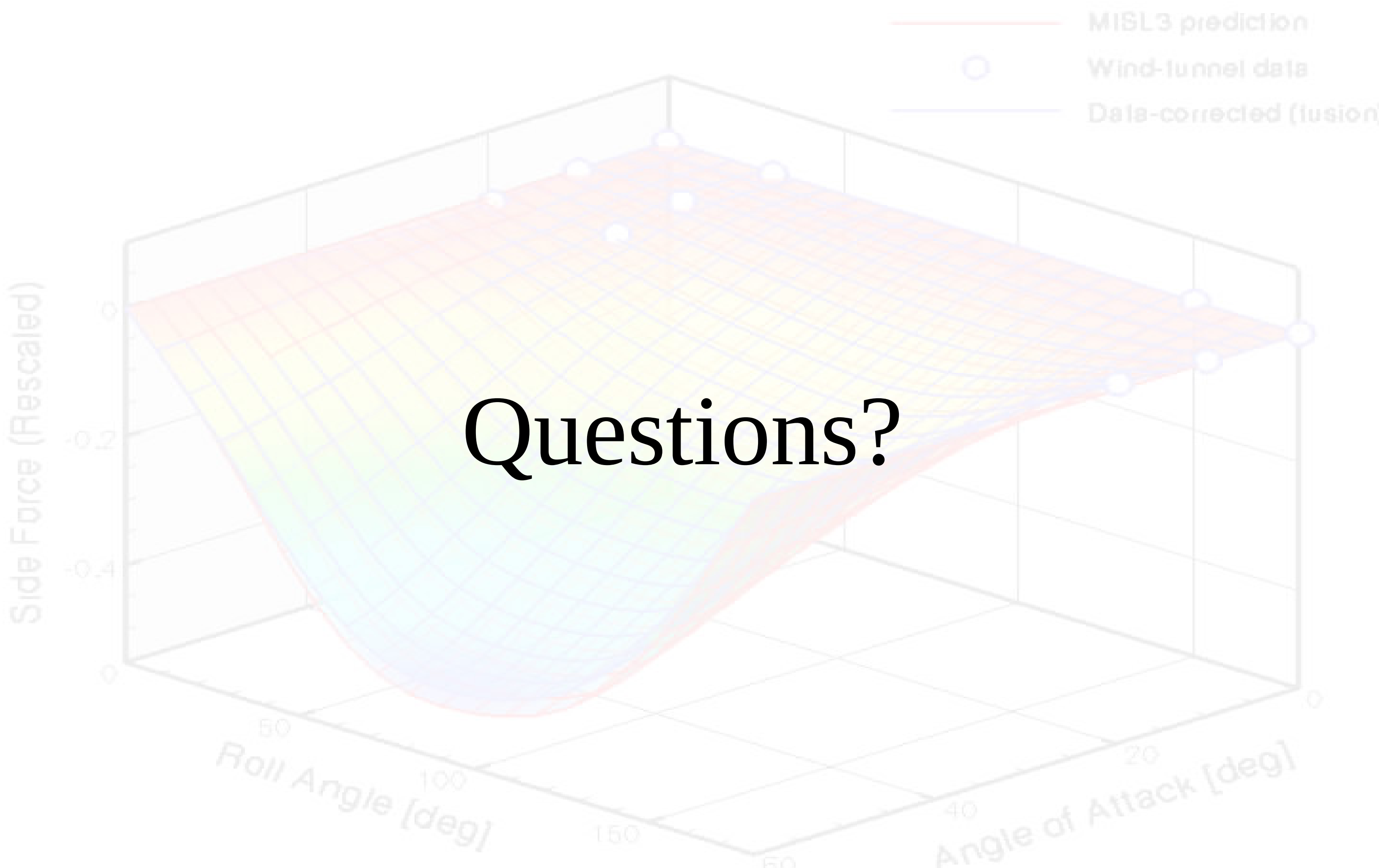


NIELSEN ENGINEERING & RESEARCH, INC.

Conclusions

- Fusion of experimental and computational data via dimensionality augmentation and RS methods
- Fully analytic, mathematical description
  - easy to use (support vector specification)
  - data structure flexibility / use of heterogeneous data sets
  - rational basis for propagating uncertainty estimates
- Assimilation of limited wind tunnel data with computational databases
  - construct smart interpolation and extrapolation schemes
  - fine-tune the results of computational analyses

Questions?



NIELSEN ENGINEERING
& RESEARCH, INC.