



2008 International ANSYS Conference

The Combination of Design of Experiments with ANSYS Analysis for the Design of a Centrifugal Compressor

Jeff Steele
Mgr., Software and Services
Impact Technologies, LLC
Rochester, New York

Mike Stanko
Sr. Engr. Associate
Praxair, Inc.
Tonawanda, NY



- History
 - Design of Experiments techniques were developed and applied to process optimization for quality control
 - Developed to replace one factor at a time (full factorial) experimentation
 - Utilized in Japan to resolve quality problems
 - Rigorous application of statistics to quality
- Noted Authors and Advocates
 - Taguchi
 - Deming and Juran
- Typical Applications
 - Applications to experimentation
 - Optimization of processes
 - Quality control
 - Develop empirical expressions to predict performance based on control and noise factors



Background and Terminology



- Design of Experiments (DoE) typically used to optimize industrial experiments where the cost of each experiment is high.
- DoE used to develop a model from an minimal/optimal set of empirical results.
- Specialized software used to design set of experiments and analyze resulting data.
- Terminology
 - **Factors** – Design Variables such as critical dimensions, operating parameters....
 - **Levels** – Values of Design Variables (Factors) across the design space.



Unique Application to Turbomachinery Analysis



- Relatively Unique Application of Design of Experiments to structural analysis of turbomachinery.
- Application of Design of Experiments techniques allows for the development of an empirical model to illustrate sensitivity of stresses to design variables using an optimized number of analysis runs.



Impeller to be Analyzed

Approx. 5.5”
diameter

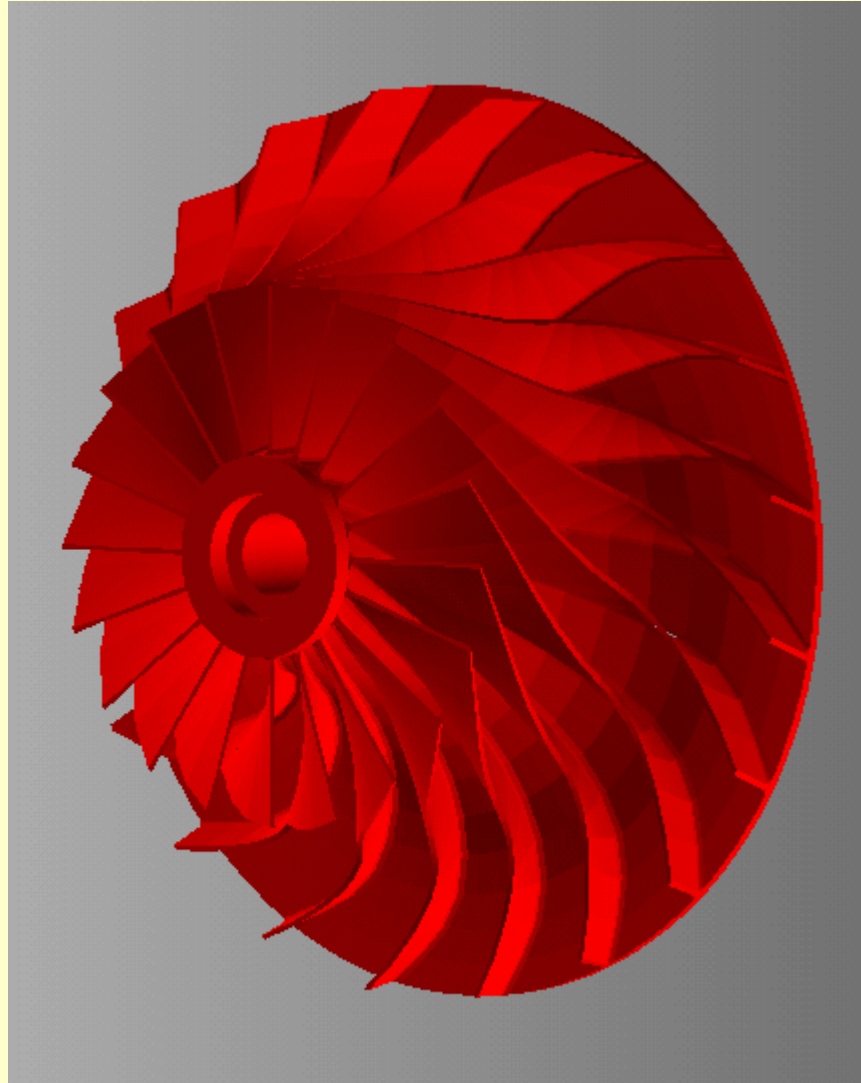
44,000 rpm

Aluminum

Design Variables to be investigated:

- Rake Angle,
- Fillet Radius,
- Blade Nominal Thickness,
- Blade Thickness Taper

were selected by the Design Engineer from experience



Factors and Levels – Central Composite Design (CCD) Utilized



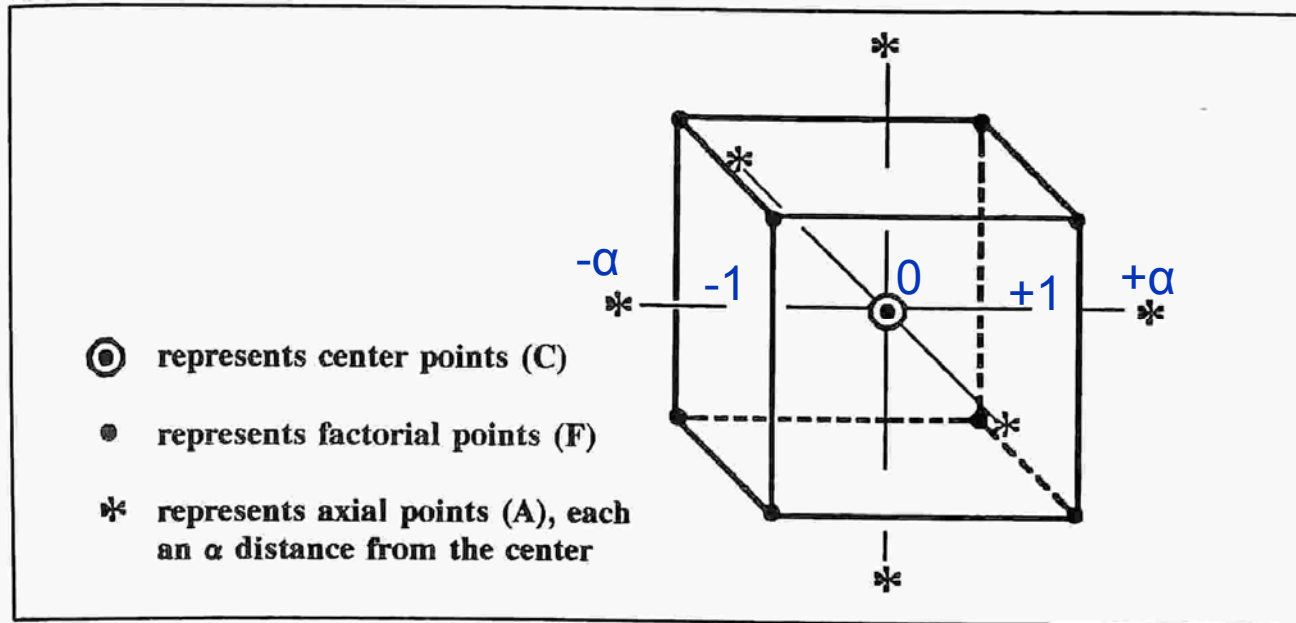
- Many Experimental Design Types are Available – Central Composite Design (CCD) Chosen
 - Good for empirical modeling; non-linear
 - Uses three levels plus two additional axial ($-\alpha$, $+\alpha$) points
- Four Factors (Impeller Design Variables) were varied:
 - Rake Angle, Fillet Radius, Blade Nominal Thickness, Blade Thickness Taper
- Initial runs with two Levels (± 1) at each of Four Factors
- Additional runs, to complete the model, were made at the nominal Level and at the axial points for each Factor
- Coded (normalized) Levels for Each Factor (Design Variable)
 - Rake Angle $-\alpha, -1, 0, +1, +\alpha$
 - Fillet Radius $-\alpha, -1, 0, +1, +\alpha$
 - Blade Thickness $-\alpha, -1, 0, +1, +\alpha$
 - Blade Taper $-\alpha, -1, 0, +1, +\alpha$
- Actual values selected by the design engineer



Four Factor, Three Level CCD Design



- Illustration of a Three Factor, Three Level (plus axial, +/- α , points) CCD Design



Note: a Four Factor, Three Level CCD Design is similar, except Four Factors; each at a maximum of five values: $-\alpha$, -1 , 0 , 1 , $+\alpha$



CCD Design – Four Factors, 3 Levels



- Full Factorial Test for Four Factors at Three Levels would require 3^4 (81) runs
- Runs 1-16 are full factorial for Four Factors at Two Levels: 2^4
- Run 17 is the center point
- Runs 18-25 include the +/- α points of the four factors

Run No.	Rake	Fillet Radius	Thickness	Taper
1	1	1	1	1
2	1	1	1	-1
3	1	1	-1	1
4	1	1	-1	-1
5	1	-1	1	1
6	1	-1	1	-1
7	1	-1	-1	1
8	1	-1	-1	-1
9	-1	1	1	1
10	-1	1	1	-1
11	-1	1	-1	1
12	-1	1	-1	-1
13	-1	-1	1	1
14	-1	-1	1	-1
15	-1	-1	-1	1
16	-1	-1	-1	-1
17	0	0	0	0
18	-1.2	0	0	0
19	1.2	0	0	0
20	0	-1.2	0	0
21	0	1.2	0	0
22	0	0	-1.2	0
23	0	0	1.2	0
24	0	0	0	-1.2
25	0	0	0	1.2

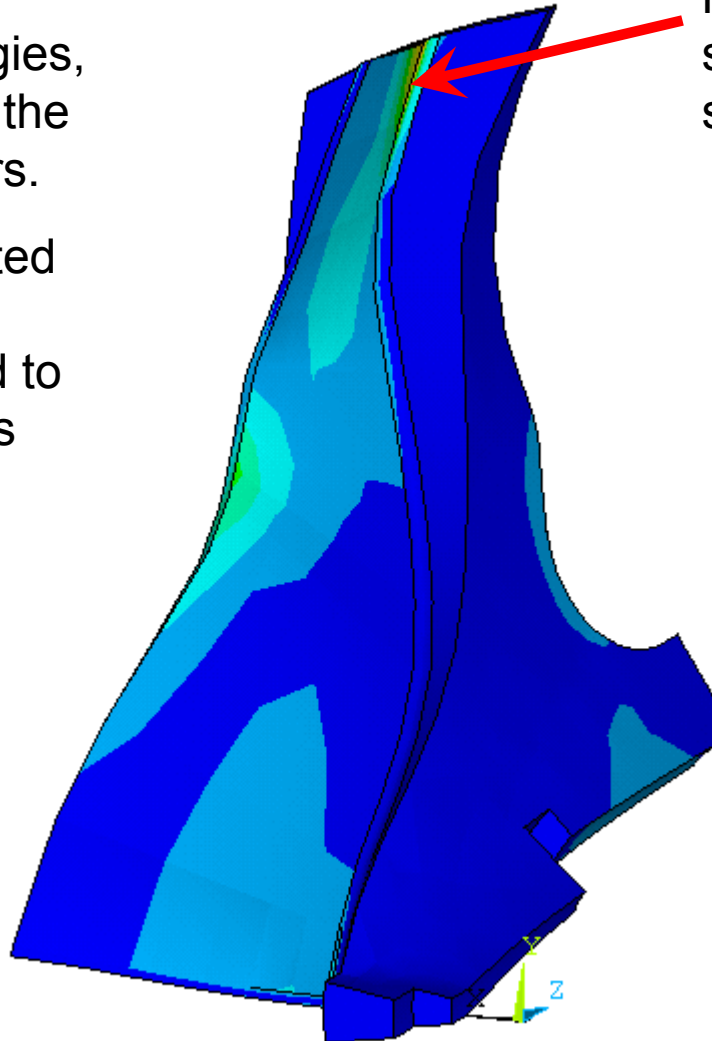


Steady Stress at Exit Used as Response



BladePro™, from Impact Technologies, was used to vary the design parameters.

BladePro generated the FEA models; ANSYS was used to perform the stress analyses



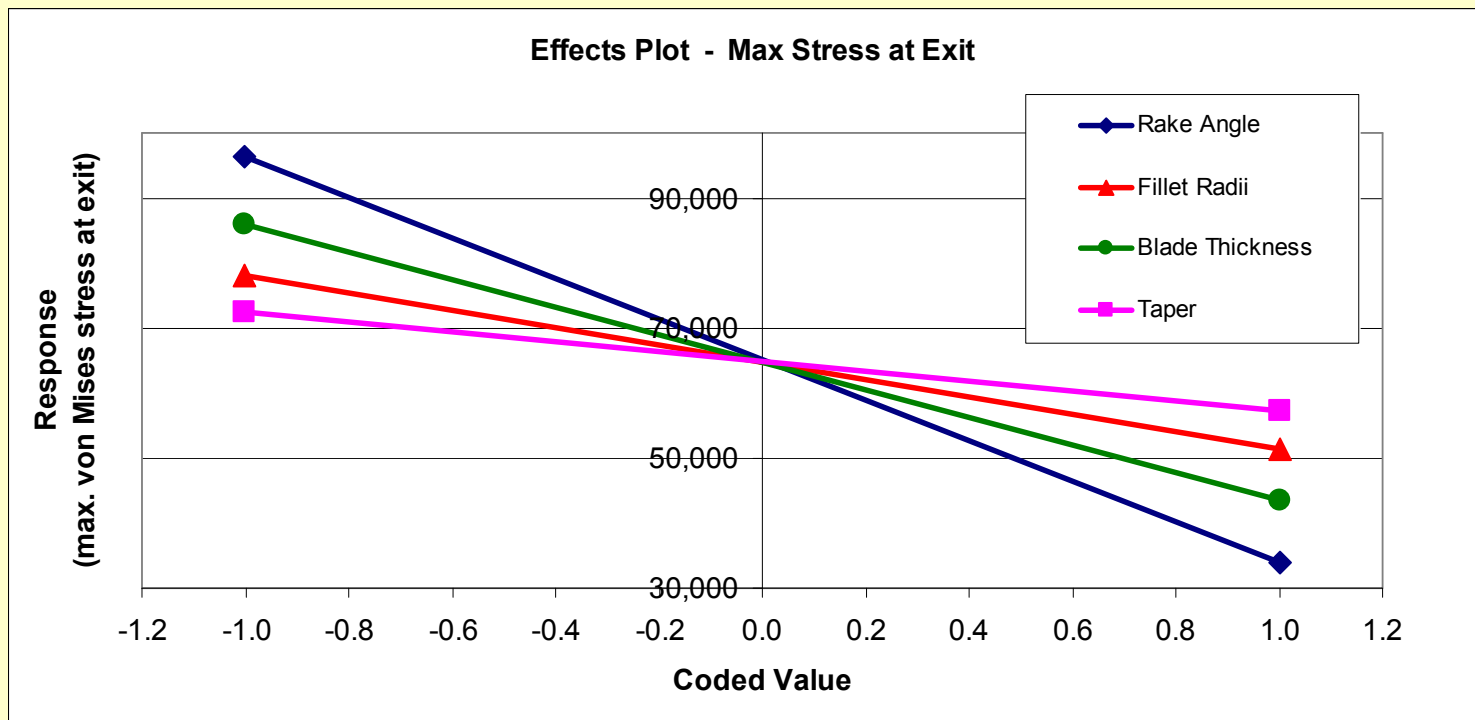
Maximum von Mises steady stress at exit was selected for DoE analysis:



Results of Screening Runs



- Normalized results showed that Rake Angle had the largest influence over steady stresses at the exit followed by: Blade Thickness, Fillet Radius and Blade Taper
- All four factors were maintained for balance of analyses
- Q-Edge™ Software used for experiment design and data fitting.



Empirical Model of Sensitivity to Design Variables (Factors)



- The model coefficients were calculated based on the responses of runs 1 - 25.
- Factor Definitions (Design Variables):
 - A Rake Angle
 - B Fillet Radius
 - C Blade Nominal Thickness
 - D Blade Thickness Taper

<u>Factor</u>	<u>Coefficient</u>
Constant	58,235.6
A	-36,062.0
B	-7,848.2
C	-16,476.0
D	-8,498.6
Asq	6,126.5
Bsq	66.1
Csq	3,341.8
Dsq	2,100.4
AB	2,568.4
AC	10,845.0
AD	6,057.0
BC	2,148.5
BD	1,248.3
CD	1,046.6

Largest Influence



Q-Edge™ software from Launsby Consulting used for experimental design and results analysis

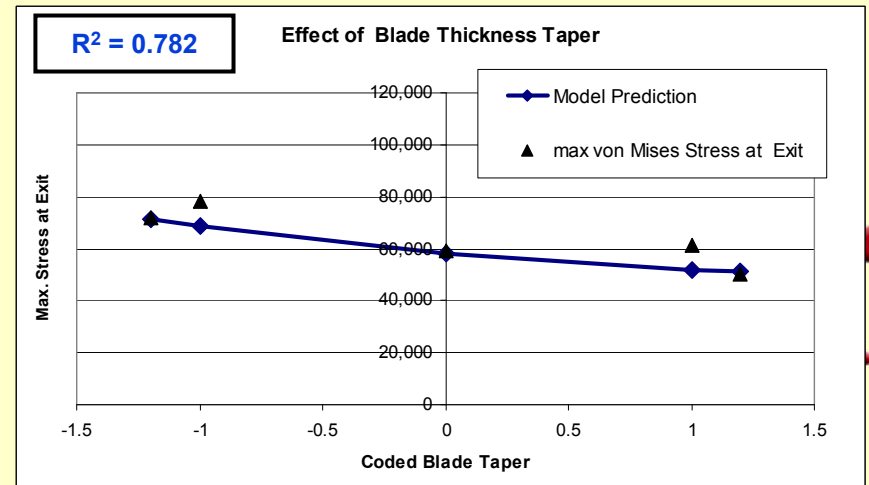
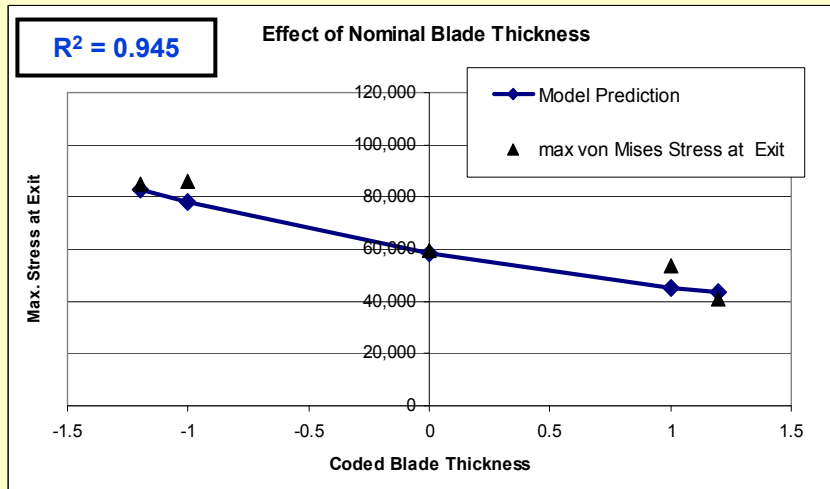
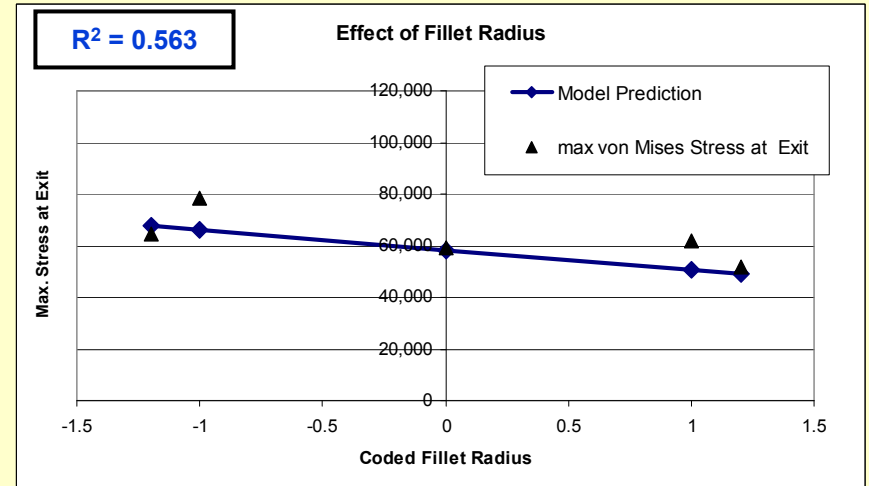
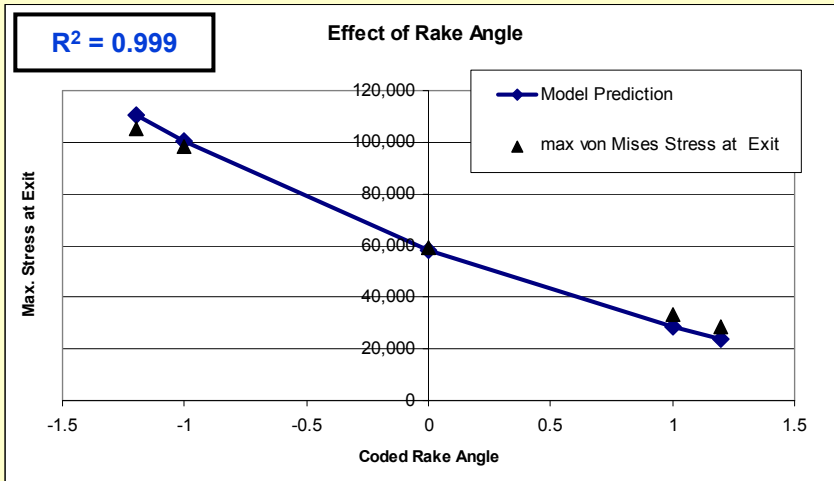
$$\sigma_{\max \text{ vM}} = 58,235.6 - 36,062.0*A - 7,848.2*B - 16,476.0*C - 8,498*D + 6,126.5*A^2 + 66.1*B^2 + 3,341.8*C^2 + 2,100.4*D^2 + 2,568.4*A*B + 10,845*A*C + 6,057*A*D + 2,148.5*B*C + 1,248.3*B*D + 1,046.6*C*D$$



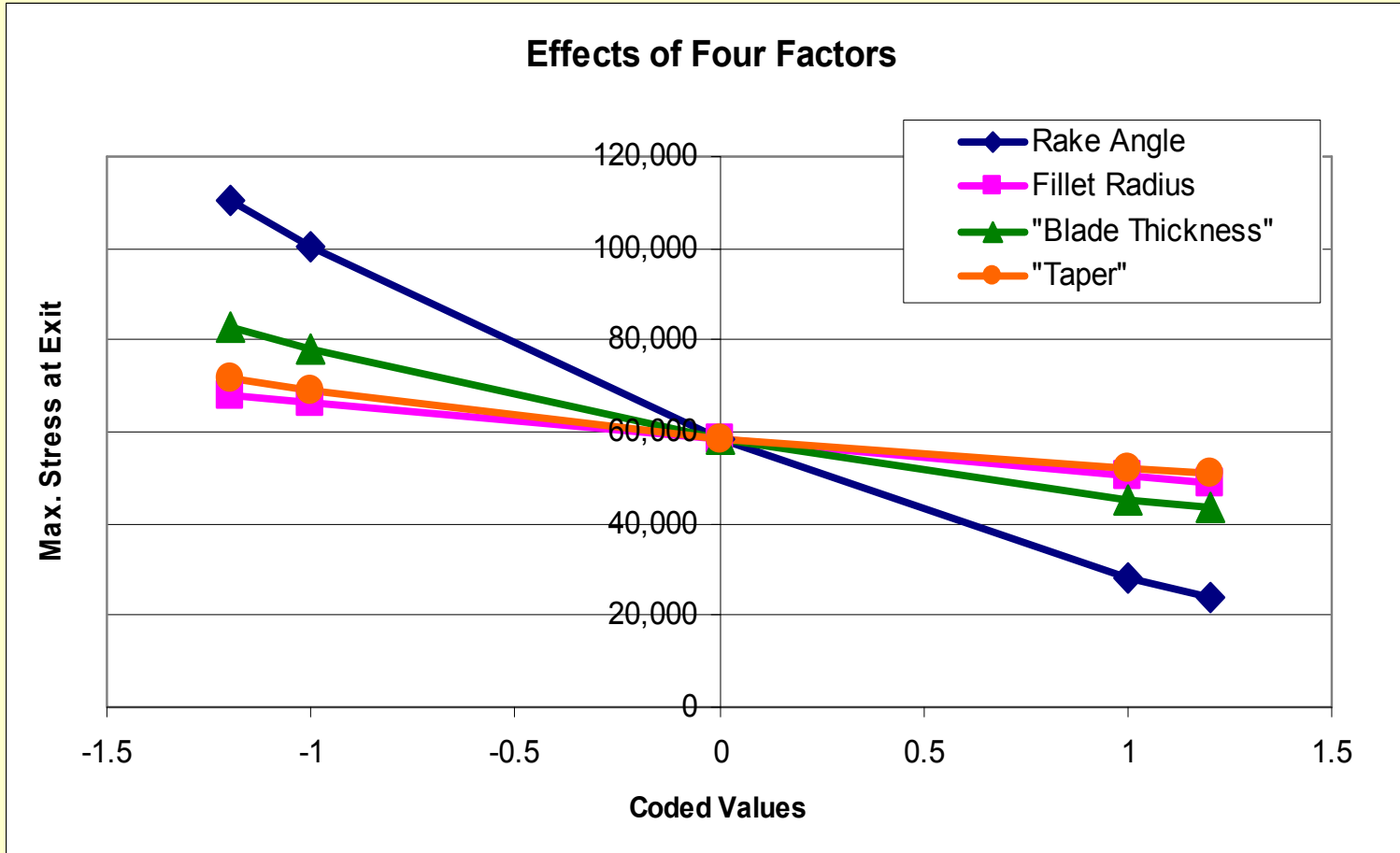
Inputs and Empirical Model Results



Q-Edge™ software from Launsby Consulting used for experimental design and results analysis



Empirical Model Predictions



Conclusions

- Design of Experiments is applicable to structural analysis of centrifugal impellers
- Reasonable results obtained for four design factors (design variables)
- Design of Experiments allows for optimizing the number of structural analyses required to generate an empirical model
- In this example, Rake Angle had the largest influence over steady stress at the exit, followed by Blade Nominal Thickness, Thickness Taper and Fillet Radius

