Using Designed Computer Experiments to Identify Important Factors in the Design of a Turbine Engine

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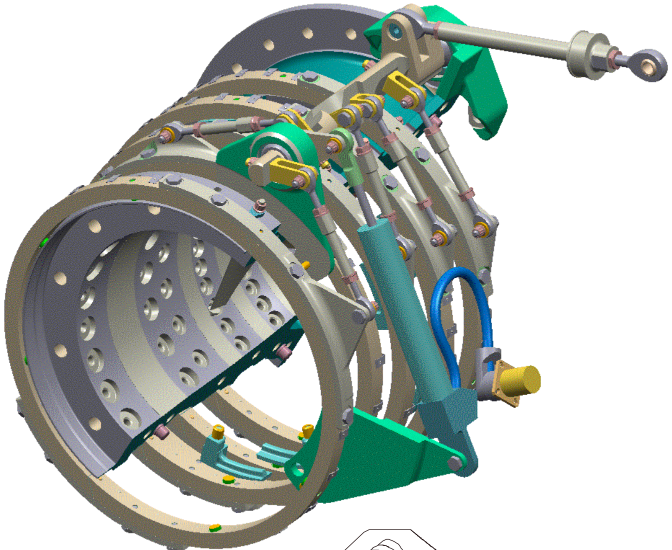
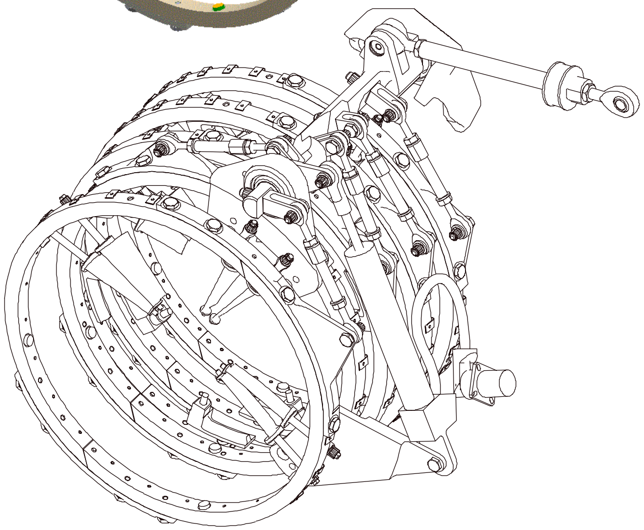
Agenda for the Talk

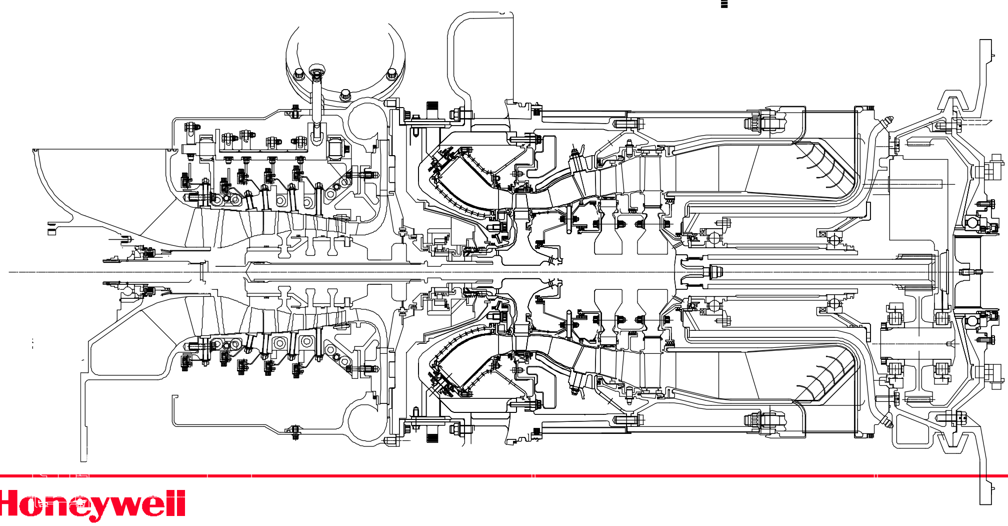
- An application of Design for Six Sigma (DFSS)
- Review of the DFSS process and goals
- Methods of DFSS
- DFSS use on a turbine engine compressor
- Large highly fractionated computer experiment
  - generation
  - analysis
- Results
- Conclusions

The LV100-5 Compressor Design

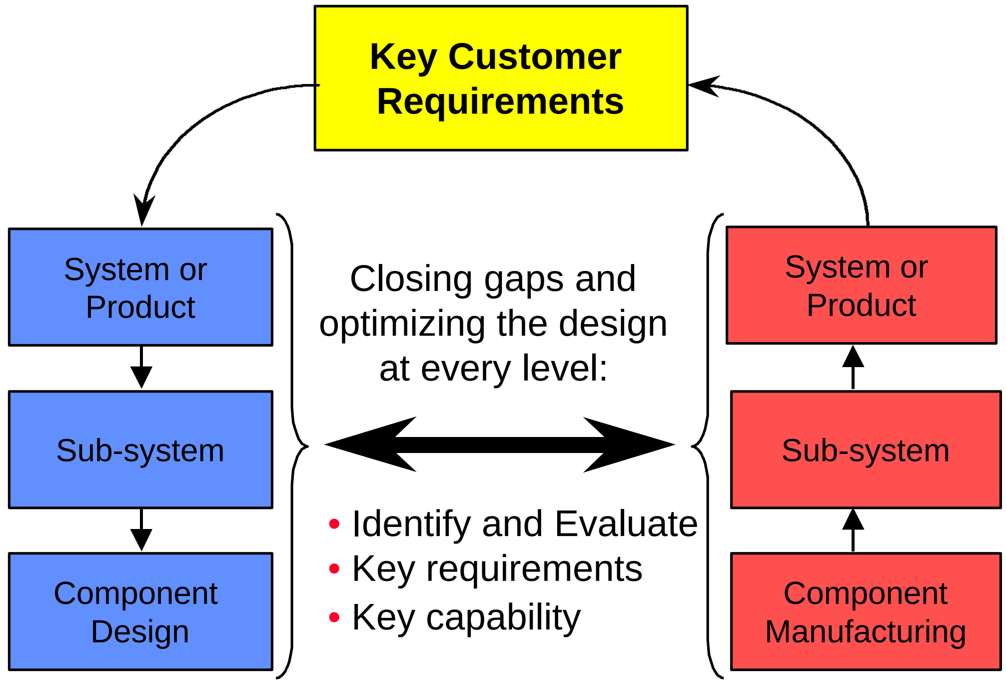
- The LV100-5 is the new turbine engine
  - for tank and mobile howitzer
- The requirements are clearly defined by the customer
- Customer requirements were flowed down to the module and component level
- Used large highly fractionated designed computer experiments
  - understand feature importance to module requirements
  - determine variation in module performance







DFSS Provides the Tools and Methods for Appropriate Design Trade-offs

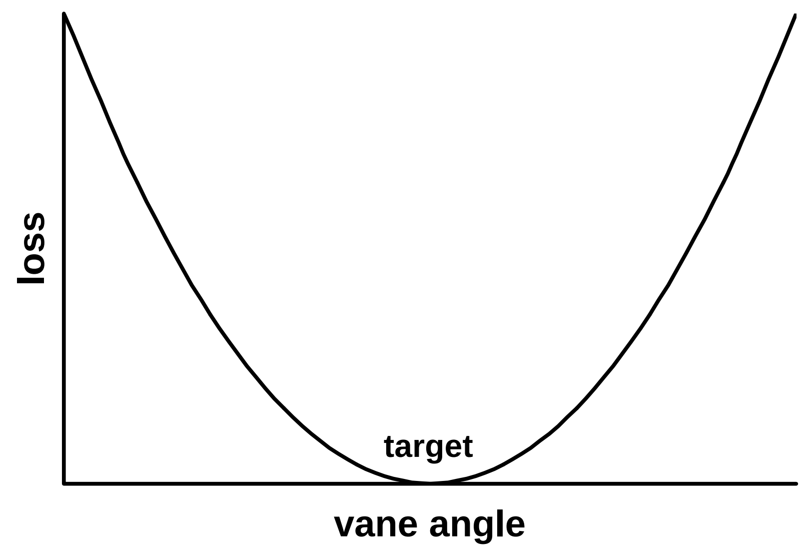


Requirement Allocation
- Mean targets
- Variance targets
- Failure rate targets

Capability Assessment
- Process capabilities
  - Mean
  - Variance
- Failure rates

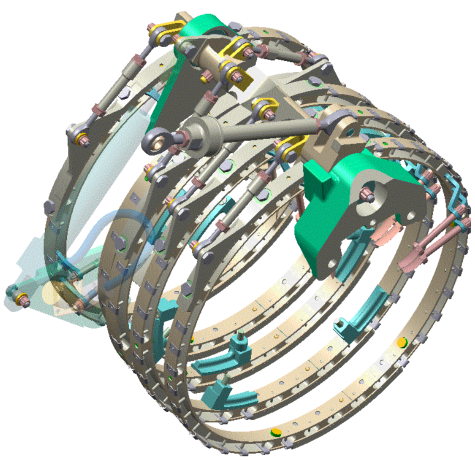
Reduced Vane Angle Variation was the Key

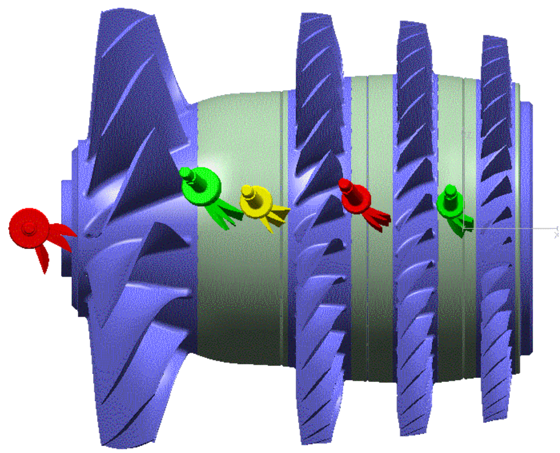
- The key requirement was compressor was vane angle variation
  - flowed down from customer
- The complex linkage and small dimensions made tolerancing challenging
- To keep cost low judicious allocation of tolerances was critical



Analytical Models were used to Determine Important Factors

- **32 factors were initially identified as potentially important**
- **Interactions between factors might exist**
- **A kinematic model was created to evaluate the effect of tolerances**
  - **model was validated with CAD package**





	factor
1	pos_vn_hl
2	sz_case_hl
3	sz_bush_od
4	sz_bush_id
5	sz_vn_stm
6	ang_lev_arm
7	vane_profile
8	len_sph_brg
9	lat_pos
10	sz_hol_brg
11	sz_uni_pin
12	sz_uni_hol
13	pos_uni_hol
14	uni_rad
15	case_uni_gap
16	pos_clevis
17	sz_clv_hol
18	pos_clv_hol
19	sz_clv_pin
20	sz_uni_rod
21	len_rod
22	sz_crnk_rod
23	con_pin
24	sz_crnk_arm_hol
25	pos_crnk_arm_hol
26	srf_bel_crnk
27	fwd_mnt
28	pos_act_stp
29	pos_mnt_stp
30	pos_aft_mnt_cas
31	pos_mnt_bell
32	lvdt

A Computer Experiment Evaluated the Factors

- To analyze 32 factors with possible interaction a resolution IV experiment was constructed
- A 2^{32-25} resolution III (128 run) was initially created
  - create a basic 2^7 design
  - assign factors to the first seven columns
  - assign remaining factors to 2 and 3 way interaction
- A full fold-over was used to create a res IV design
  - a second fraction was added to the first
  - the signs of each factor in the basic design was reversed
- The second fraction breaks the alias of two-way interactions with main effects
- Does not necessarily produce a minimum aberration design

The Process is Illustrated with Seven Factors

- **Create a 2^{7-4} res III design - principal fraction**

run	A (Basic Design)	B (Basic Design)	C (Basic Design)	D = AB	E = AC	F = CB	G = ABC
1	–	–	–	+	+	+	–
2	+	–	–	–	–	+	+
3	–	+	–	–	–	–	+
4	+	+	–	+	+	–	–
5	–	–	+	+	+	–	+
6	+	–	+	–	–	–	–
7	–	+	+	–	–	+	–
8	+	+	+	+	+	+	+

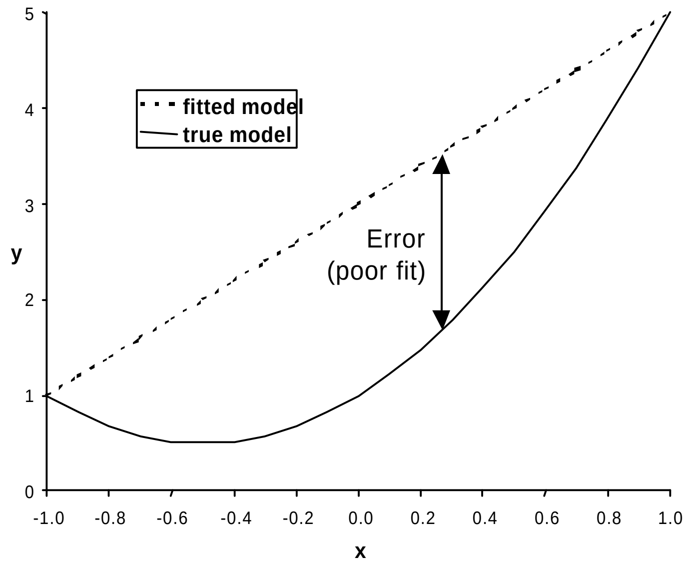
- **Add the alternative fraction reversing signs on generators with an odd number of letters**

run	A (Basic Design)	B (Basic Design)	C (Basic Design)	D = -AB	E = -AC	F = -CB	G = ABC
9	+	+	+	–	–	–	+
10	–	+	+	+	+	–	–
11	+	–	+	+	+	+	–
12	–	–	+	–	–	+	+
13	+	+	–	–	–	+	–
14	–	+	–	+	+	+	+
15	+	–	–	+	+	–	+
16	–	–	–	–	–	–	–

- **Generators of the first fraction *I=ABC, I=ACE, I=BCF,* and *I=ABCG***
- **Generators of the second fraction *I=-ABC, I=-ACE, I=-BCF,* and *I=ABCG***
- **See Montgomery and Runger (1996) JQT v24 for more detail**

The Analysis of the Results

- **The analysis of computer experiment do not have statistical significance**
  - **the error is bias error not random error**
- **Engineering judgement is used to determine important effects**
- **Taylor series approximation justifies simple model**



$$y = b_0 + b_1 x_1 + b_2 x_2 + \ldots + b_{12} x_1 x_2 + \ldots$$

$$y = f(0) + \frac{\partial f}{\partial x_1} x_1 + \frac{\partial f}{\partial x_2} x_2 + \ldots + \frac{\partial^2 f}{\partial x_1 \partial x_2} x_1 x_2 + \ldots$$

The Design is Large

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
2	-	+	+	+	+	+	+	-	-	-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	+	+	+
3	+	-	+	+	+	+	+	-	+	+	+	+	+	-	-	-	-	-	+	+	+	+	+	+	+	+	+	+	-	-	+	+
4	-	-	+	+	+	+	+	+	-	-	-	-	-	-	-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	-	+	+
5	+	+	-	+	+	+	+	+	-	+	+	+	+	-	+	+	+	+	-	-	-	-	+	+	+	+	+	+	-	-	-	+
6	-	+	-	+	+	+	+	-	+	-	-	-	-	-	+	+	+	+	-	-	-	-	+	+	+	+	+	+	+	-	-	+
7	+	-	-	+	+	+	+	-	-	+	+	+	+	+	-	-	-	-	-	-	-	-	+	+	+	+	+	+	+	+	-	+
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148	+	+	-	-	+	-	-	-	+	+	-	+	+	+	+	-	+	+	-	+	-	-	+	-	-	+	+	-	-	+	+	+
149	-	-	+	-	+	-	-	-	+	-	+	-	-	+	-	+	-	-	+	-	+	+	+	-	-	+	+	-	+	+	-	+
150	+	-	+	-	+	-	-	+	-	+	-	+	+	+	-	+	-	-	+	-	+	+	+	-	-	+	+	-	-	+	-	+
151	-	+	+	-	+	-	-	+	+	-	+	-	-	-	+	-	+	+	+	-	+	+	+	-	-	+	+	-	-	-	-	+
152	+	+	+	-	+	-	-	-	-	+	-	+	+	-	+	-	+	+	+	-	+	+	+	-	-	+	+	-	+	-	-	+
153	-	-	-	+	+	-	-	-	-	+	+	-	-	-	+	+	-	-	+	+	-	-	-	+	+	+	+	-	-	+	-	-
154	+	-	-	+	+	-	-	+	+	-	-	+	+	-	+	+	-	-	+	+	-	-	-	+	+	+	+	-	+	+	-	-
155	-	+	-	+	+	-	-	+	-	+	+	-	-	+	-	-	+	+	+	+	-	-	-	+	+	+	+	-	+	-	-	-
156	+	+	-	+	+	-	-	-	+	-	-	+	+	+	-	-	+	+	+	+	-	-	-	+	+	+	+	-	-	-	-	-
157	-	-	+	+	+	-	-	-	+	+	+	-	-	+	+	+	-	-	-	-	+	+	-	+	+	+	+	-	+	-	+	-
158	+	-	+	+	+	-	-	+	-	-	-	+	+	+	+	+	-	-	-	-	+	+	-	+	+	+	+	-	-	-	+	-
159	-	+	+	+	+	-	-	+	+	+	+	-	-	-	-	-	+	+	-	-	+	+	-	+	+	+	+	-	-	+	+	-
160	+	+	+	+	+	-	-	-	-	-	-	+	+	-	-	-	+	+	-	-	+	+	-	+	+	+	+	-	+	+	+	-
161	-	-	-	-	-	+	-	-	-	-	-	+	-	-	-	-	+	-	-	-	+	-	-	+	-	+	-	+	-	-	-	+
162	+	-	-	-	-	+	-	+	+	+	+	-	+	-	-	-	+	-	-	-	+	-	-	+	-	+	-	+	+	-	-	+
163	-	+	-	-	-	+	-	+	-	-	-	+	-	+	+	+	-	+	-	-	+	-	-	+	-	+	-	+	+	+	-	+
164	+	+	-	-	-	+	-	-	+	+	+	-	+	+	+	+	-	+	-	-	+	-	-	+	-	+	-	+	-	+	-	+
165	-	-	+	-	-	+	-	-	+	-	-	+	-	+	-	-	+	-	+	+	-	+	-	+	-	+	-	+	+	+	+	+
166	+	-	+	-	-	+	-	+	-	+	+	-	+	+	-	-	+	-	+	+	-	+	-	+	-	+	-	+	-	+	+	+
167	-	+	+	-	-	+	-	+	+	-	-	+	-	-	+	+	-	+	+	+	-	+	-	+	-	+	-	+	-	-	+	+
168	+	+	+	-	-	+	-	-	-	+	+	-	+	-	+	+	-	+	+	+	-	+	-	+	-	+	-	+	+	-	+	+
169	-	-	-	+	-	+	-	-	-	+	-	+	-	-	+	-	+	-	+	-	+	-	+	-	+	+	-	+	-	+	+	-
170	+	-	-	+	-	+	-	+	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	+	-	+	+	+	+	-
171	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	+	-	+	-	+	-	+	+	-	+	+	-	+	-
172	+	+	-	+	-	+	-	-	+	-	+	-	+	+	-	+	-	+	+	-	+	-	+	-	+	+	-	+	-	-	+	-
173	-	-	+	+	-	+	-	-	+	+	-	+	-	+	+	-	+	-	-	+	-	+	+	-	+	+	-	+	+	-	-	-
174	+	-	+	+	-	+	-	+	-	-	+	-	+	+	+	-	+	-	-	+	-	+	+	-	+	+	-	+	-	-	-	-
175	-	+	+	+	-	+	-	+	+	+	-	+	-	-	-	+	-	+	-	+	-	+	+	-	+	+	-	+	-	+	-	-
176	+	+	+	+	-	+	-	-	-	-	+	-	+	-	-	+	-	+	-	+	-	+	+	-	+	+	-	+	+	+	-	-
177	-	-	-	-	+	+	-	-	-	-	+	+	-	-	-	+	+	-	-	+	+	-	+	+	-	-	+	+	-	-	+	-
178	+	-	-	-	+	+	-	+	+	+	-	-	+	-	-	+	+	-	-	+	+	-	+	+	-	-	+	+	+	-	+	-
179	-	+	-	-	+	+	-	+	-	-	+	+	-	+	+	-	-	+	-	+	+	-	+	+	-	-	+	+	+	+	+	-
180	+	+	-	-	+	+	-	-	+	+	-	-	+	+	+	-	-	+	-	+	+	-	+	+	-	-	+	+	-	+	+	-
181	-	-	+	-	+	+	-	-	+	-	+	+	-	+	-	+	+	-	+	-	-	+	+	+	-	-	+	+	+	+	-	-
182	+	-	+	-	+	+	-	+	-	+	-	-	+	+	-	+	+	-	+	-	-	+	+	+	-	-	+	+	-	+	-	-
183	-	+	+	-	+	+	-	+	+	-	+	+	-	-	+	-	-	+	+	-	-	+	+	+	-	-	+	+	-	-	-	-
184	+	+	+	-	+	+	-	-	-	+	-	-	+	-	+	-	-	+	+	-	-	+	+	+	-	-	+	+	+	-	-	-
185	-	-	-	+	+	+	-	-	-	+	+	+	-	-	+	+	+	-	+	+	+	-	-	-	+	-	+	+	-	+	-	+
186	+	-	-	+	+	+	-	+	+	-	-	-	+	-	+	+	+	-	+	+	+	-	-	-	+	-	+	+	+	+	-	+
187	-	+	-	+	+	+	-	+	-	+	+	+	-	+	-	-	-	+	+	+	+	-	-	-	+	-	+	+	+	-	-	+
188	+	+	-	+	+	+	-	-	+	-	-	-	+	+	-	-	-	+	+	+	+	-	-	-	+	-	+	+	-	-	-	+
189	-	-	+	+	+	+	-	-	+	+	+	+	-	+	+	+	+	-	-	-	-	+	-	-	+	-	+	+	+	-	+	+
190	+	-	+	+	+	+	-	+	-	-	-	-	+	+	+	+	+	-	-	-	-	+	-	-	+	-	+	+	-	-	+	+
191	-	+	+	+	+	+	-	+	+	+	+	+	-	-	-	-	-	+	-	-	-	+	-	-	+	-	+	+	-	+	+	+
192	+	+	+	+	+	+	-	-	-	-	-	-	+	-	-	-	-	+	-	-	-	+	-	-	+	-	+	+	+	+	+	+

The Design is Large - the Second Portion

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
65	+	+	+	+	+	+	-	+	+	+	+	+	-	+	+	+	+	-	+	+	+	-	+	+	-	+	-	-	+	+	+	+
66	-	+	+	+	+	+	-	-	-	-	-	-	+	+	+	+	+	-	+	+	+	-	+	+	-	+	-	-	-	+	+	+
67	+	-	+	+	+	+	-	-	+	+	+	+	-	-	-	-	-	+	+	+	+	-	+	+	-	+	-	-	-	-	+	+
68	-	-	+	+	+	+	-	+	-	-	-	-	+	-	-	-	-	+	+	+	+	-	+	+	-	+	-	-	+	-	+	+
69	+	+	-	+	+	+	-	+	-	+	+	+	-	-	+	+	+	-	-	-	-	+	+	+	-	+	-	-	-	-	-	+
70	-	+	-	+	+	+	-	-	+	-	-	-	+	-	+	+	+	-	-	-	-	+	+	+	-	+	-	-	+	-	-	+
71	+	-	-	+	+	+	-	-	-	+	+	+	-	+	-	-	-	+	-	-	-	+	+	+	-	+	-	-	+	+	-	+
72	-	-	-	+	+	+	-	+	+	-	-	-	+	+	-	-	-	+	-	-	-	+	+	+	-	+	-	-	-	+	-	+
73	+	+	+	-	+	+	-	+	+	-	+	+	-	+	-	+	+	-	-	+	+	-	-	-	+	+	-	-	+	-	-	-
74	-	+	+	-	+	+	-	-	-	+	-	-	+	+	-	+	+	-	-	+	+	-	-	-	+	+	-	-	-	-	-	-
75	+	-	+	-	+	+	-	-	+	-	+	+	-	-	+	-	-	+	-	+	+	-	-	-	+	+	-	-	-	+	-	-
76	-	-	+	-	+	+	-	+	-	+	-	-	+	-	+	-	-	+	-	+	+	-	-	-	+	+	-	-	+	+	-	-
77	+	+	-	-	+	+	-	+	-	-	+	+	-	-	-	+	+	-	+	-	-	+	-	-	+	+	-	-	-	+	+	-
78	-	+	-	-	+	+	-	-	+	+	-	-	+	-	-	+	+	-	+	-	-	+	-	-	+	+	-	-	+	+	+	-
79	+	-	-	-	+	+	-	-	-	-	+	+	-	+	+	-	-	+	+	-	-	+	-	-	+	+	-	-	+	-	+	-
80	-	-	-	-	+	+	-	+	+	+	-	-	+	+	+	-	-	+	+	-	-	+	-	-	+	+	-	-	-	-	+	-
81	+	+	+	+	-	+	-	+	+	+	-	+	-	+	+	-	+	-	+	-	+	-	-	+	-	-	+	-	+	+	-	-
82	-	+	+	+	-	+	-	-	-	-	+	-	+	+	+	-	+	-	+	-	+	-	-	+	-	-	+	-	-	+	-	-
83	+	-	+	+	-	+	-	-	+	+	-	+	-	-	-	+	-	+	+	-	+	-	-	+	-	-	+	-	-	-	-	-
84	-	-	+	+	-	+	-	+	-	-	+	-	+	-	-	+	-	+	+	-	+	-	-	+	-	-	+	-	+	-	-	-
85	+	+	-	+	-	+	-	+	-	+	-	+	-	-	+	-	+	-	-	+	-	+	-	+	-	-	+	-	-	-	+	-
86	-	+	-	+	-	+	-	-	+	-	+	-	+	-	+	-	+	-	-	+	-	+	-	+	-	-	+	-	+	-	+	-
87	+	-	-	+	-	+	-	-	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	-	+	-	+	+	+	-
88	-	-	-	+	-	+	-	+	+	-	+	-	+	+	-	+	-	+	-	+	-	+	-	+	-	-	+	-	-	+	+	-
89	+	+	+	-	-	+	-	+	+	-	-	+	-	+	-	-	+	-	-	-	+	-	+	-	+	-	+	-	+	-	+	+
90	-	+	+	-	-	+	-	-	-	+	+	-	+	+	-	-	+	-	-	-	+	-	+	-	+	-	+	-	-	-	+	+
91	+	-	+	-	-	+	-	-	+	-	-	+	-	-	+	+	-	+	-	-	+	-	+	-	+	-	+	-	-	+	+	+
92	-	-	+	-	-	+	-	+	-	+	+	-	+	-	+	+	-	+	-	-	+	-	+	-	+	-	+	-	+	+	+	+
93	+	+	-	-	-	+	-	+	-	-	-	+	-	-	-	-	+	-	+	+	-	+	+	-	+	-	+	-	-	+	-	+
94	-	+	-	-	-	+	-	-	+	+	+	-	+	-	-	-	+	-	+	+	-	+	+	-	+	-	+	-	+	+	-	+
95	+	-	-	-	-	+	-	-	-	-	-	+	-	+	+	+	-	+	+	+	-	+	+	-	+	-	+	-	+	-	-	+
96	-	-	-	-	-	+	-	+	+	+	+	-	+	+	+	+	-	+	+	+	-	+	+	-	+	-	+	-	-	-	-	+
97	+	+	+	+	+	-	-	+	+	+	+	-	-	+	+	+	-	-	+	+	-	-	+	-	-	-	-	+	+	+	+	-
98	-	+	+	+	+	-	-	-	-	-	-	+	+	+	+	+	-	-	+	+	-	-	+	-	-	-	-	+	-	+	+	-
99	+	-	+	+	+	-	-	-	+	+	+	-	-	-	-	-	+	+	+	+	-	-	+	-	-	-	-	+	-	-	+	-
100	-	-	+	+	+	-	-	+	-	-	-	+	+	-	-	-	+	+	+	+	-	-	+	-	-	-	-	+	+	-	+	-
101	+	+	-	+	+	-	-	+	-	+	+	-	-	-	+	+	-	-	-	-	+	+	+	-	-	-	-	+	-	-	-	-
102	-	+	-	+	+	-	-	-	+	-	-	+	+	-	+	+	-	-	-	-	+	+	+	-	-	-	-	+	+	-	-	-
103	+	-	-	+	+	-	-	-	-	+	+	-	-	+	-	-	+	+	-	-	+	+	+	-	-	-	-	+	+	+	-	-
104	-	-	-	+	+	-	-	+	+	-	-	+	+	+	-	-	-	+	+	-	-	+	+	-	-	-	-	+	-	-	+	-
105	+	+	+	-	+	-	-	+	+	-	+	-	-	+	-	+	-	-	-	+	-	-	-	+	+	-	-	+	+	-	-	+
106	-	+	+	-	+	-	-	-	-	+	-	+	+	+	-	+	-	-	-	+	-	-	-	+	+	-	-	+	-	-	-	+
107	+	-	+	-	+	-	-	-	+	-	+	-	-	-	+	-	+	+	-	+	-	-	-	+	+	-	-	+	-	+	-	+
108	-	-	+	-	+	-	-	+	-	+	-	+	+	-	+	-	+	+	-	+	-	-	-	+	+	-	-	+	+	+	-	+
109	+	+	-	-	+	-	-	+	-	-	+	-	-	-	-	+	-	-	+	-	+	+	-	+	+	-	-	+	-	+	+	+
110	-	+	-	-	+	-	-	-	+	+	-	+	+	-	-	+	-	-	+	-	+	+	-	+	+	-	-	+	+	+	+	+
111	+	-	-	-	+	-	-	-	-	-	+	-	-	+	+	-	+	+	+	-	+	+	-	+	+	-	-	+	+	-	+	+
112	-	-	-	-	+	-	-	+	+	+	-	+	+	+	+	-	+	+	+	-	+	+	-	+	+	-	-	+	-	-	+	+
113	+	+	+	+	-	-	-	+	+	+	-	-	-	+	+	-	-	-	+	-	-	-	-	-	-	+	+	+	+	+	-	+
114	-	+	+	+	-	-	-	-	-	-	+	+	+	+	+	-	-	-	+	-	-	-	-	-	-	+	+	+	-	+	-	+
115	+	-	+	+	-	-	-	-	+	+	-	-	-	-	-	+	+	+	+	-	-	-	-	-	-	+	+	+	-	-	-	+
116	-	-	+	+	-	-	-	+	-	-	+	+	+	-	-	+	+	+	+	-	-	-	-	-	-	+	+	+	+	-	-	+
117	+	+	-	+	-	-	-	+	-	+	-	-	-	-	+	-	-	-	-	+	+	+	-	-	-	+	+	+	-	-	+	+
118	-	+	-	+	-	-	-	-	+	-	+	+	+	-	+	-	-	-	-	+	+	+	-	-	-	+	+	+	+	-	+	+
119	+	-	-	+	-	-	-	-	-	+	-	-	-	+	-	+	+	+	-	+	+	+	-	-	-	+	+	+	+	+	+	+
120	-	-	-	+	-	-	-	+	+	-	+	+	+	+	-	+	+	+	-	+	+	+	-	-	-	+	+	+	-	+	+	+
121	+	+	+	-	-	-	-	+	+	-	-	-	-	+	-	-	-	-	-	-	-	-	+	+	+	+	+	+	+	-	+	-
122	-	+	+	-	-	-	-	-	-	+	+	+	+	+	-	-	-	-	-	-	-	-	+	+	+	+	+	+	-	-	+	-
123	+	-	+	-	-	-	-	-	+	-	-	-	-	-	+	+	+	+	-	-	-	-	+	+	+	+	+	+	-	+	+	-
124	-	-	+	-	-	-	-	+	-	+	+	+	+	-	+	+	+	+	-	-	-	-	+	+	+	+	+	+	-	+	+	-
125	+	+	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	+	+	+	+	+	+	+	+	+	+	-	+	-	-
126	-	+	-	-	-	-	-	-	+	+	+	+	-	-	-	-	-	+	+	+	+	+	+	+	+	+	+	-	+	-	-	-
127	+	-	-	-	-	-	-	-	-	-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	-
128	-	-	-	-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	-	-	-

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
193	-	-	-	-	-	-	+	-	-	-	-	-	+	-	-	-	-	+	-	-	-	+	-	-	+	-	+	+	-	-	-	-
194	+	-	-	-	-	-	+	+	+	+	+	+	-	-	-	-	-	+	-	-	-	+	-	-	+	-	+	+	+	-	-	-
195	-	+	-	-	-	-	+	+	-	-	-	-	+	+	+	+	+	-	-	-	-	+	-	-	+	-	+	+	+	+	-	-
196	+	+	-	-	-	-	+	-	+	+	+	+	-	+	+	+	+	-	-	-	-	+	-	-	+	-	+	+	-	+	-	-
197	-	-	+	-	-	-	+	-	+	-	-	-	+	+	-	-	-	+	+	+	+	-	-	-	+	-	+	+	+	+	+	-
198	+	-	+	-	-	-	+	+	-	+	+	+	-	+	-	-	-	+	+	+	+	-	-	-	+	-	+	+	-	+	+	-
199	-	+	+	-	-	-	+	+	+	-	-	-	+	-	+	+	+	-	+	+	+	-	-	-	+	-	+	+	-	-	+	-
200	+	+	+	-	-	-	+	-	-	+	+	+	-	-	+	+	+	-	+	+	+	-	-	-	+	-	+	+	+	-	+	-
201	-	-	-	+	-	-	+	-	-	+	-	-	+	-	+	-	-	+	+	-	-	+	+	+	-	-	+	+	-	+	+	+
202	+	-	-	+	-	-	+	+	+	-	+	+	-	-	+	-	-	+	+	-	-	+	+	+	-	-	+	+	+	+	+	+
203	-	+	-	+	-	-	+	+	-	+	-	-	+	+	-	+	+	-	+	-	-	+	+	+	-	-	+	+	+	-	+	+
204	+	+	-	+	-	-	+	-	+	-	+	+	-	+	-	+	+	-	+	-	-	+	+	+	-	-	+	+	-	-	+	+
205	-	-	+	+	-	-	+	-	+	+	-	-	+	+	+	-	-	+	-	+	+	-	+	+	-	-	+	+	+	-	-	+
206	+	-	+	+	-	-	+	+	-	-	+	+	-	+	+	-	-	+	-	+	+	-	+	+	-	-	+	+	-	-	-	+
207	-	+	+	+	-	-	+	+	+	+	-	-	+	-	-	+	+	-	-	+	+	-	+	+	-	-	+	+	-	+	-	+
208	+	+	+	+	-	-	+	-	-	-	+	+	-	-	-	+	+	-	-	+	+	-	+	+	-	-	+	+	+	+	-	+
209	-	-	-	-	+	-	+	-	-	-	+	-	+	-	-	+	-	+	-	+	-	+	+	-	+	+	-	+	-	-	+	+
210	+	-	-	-	+	-	+	+	+	+	-	+	-	-	-	+	-	+	-	+	-	+	+	-	+	+	-	+	+	-	+	+
211	-	+	-	-	+	-	+	+	-	-	+	-	+	+	+	-	+	-	-	+	-	+	+	-	+	+	-	+	+	+	+	+
212	+	+	-	-	+	-	+	-	+	+	-	+	-	+	+	-	+	-	-	+	-	+	+	-	+	+	-	+	-	+	+	+
213	-	-	+	-	+	-	+	-	+	-	+	-	+	+	-	+	-	+	+	-	+	-	+	-	+	+	-	+	+	+	-	+
214	+	-	+	-	+	-	+	+	-	+	-	+	-	+	-	+	-	+	+	-	+	-	+	-	+	+	-	+	-	+	-	+
215	-	+	+	-	+	-	+	+	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	+	-	+	-	-	-	+
216	+	+	+	-	+	-	+	-	-	+	-	+	-	-	+	-	+	-	+	-	+	-	+	-	+	+	-	+	+	-	-	+
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229	-	-	+	-	-	+	+	-	+	-	-	+	+	+	-	-	+	+	+	+	-	-	-	+	+	+	+	-	+	+	+	+
230	+	-	+	-	-	+	+	+	-	+	+	-	-	+	-	-	+	+	+	+	-	-	-	+	+	+	+	-	-	+	+	+
231	-	+	+	-	-	+	+	+	+	-	-	+	+	-	+	+	-	-	+	+	-	-	-	+	+	+	+	-	-	-	+	+
232	+	+	+	-	-	+	+	-	-	+	+	-	-	-	+	+	-	-	+	+	-	-	-	+	+	+	+	-	+	-	+	+
233	-	-	-	+	-	+	+	-	-	+	-	+	+	-	+	-	+	+	+	-	+	+	+	-	-	+	+	-	-	+	+	-
234	+	-	-	+	-	+	+	+	+	-	+	-	-	-	+	-	+	+	+	-	+	+	+	-	-	+	+	-	+	+	+	-
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238	+	-	+	+	-	+	+	+	-	-	+	-	-	+	+	-	+	+	-	+	-	-	+	-	-	+	+	-	-	-	-	-
239	-	+	+	+	-	+	+	+	+	+	-	+	+	-	-	+	-	-	-	+	-	-	+	-	-	+	+	-	-	+	-	-
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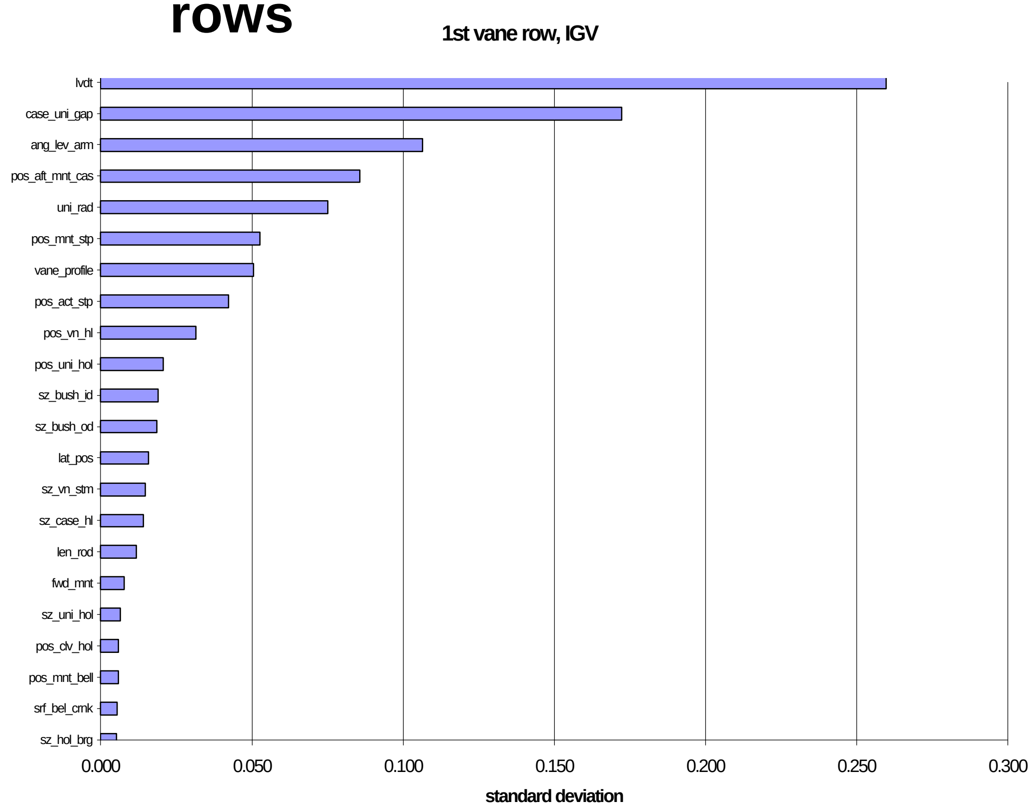
256	+	+	+	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	+	+

Analysis Used Standard Techniques

- **The study identified influential factors affecting CVG performance**
- **Factors with large influence were consistent across all vane rows**

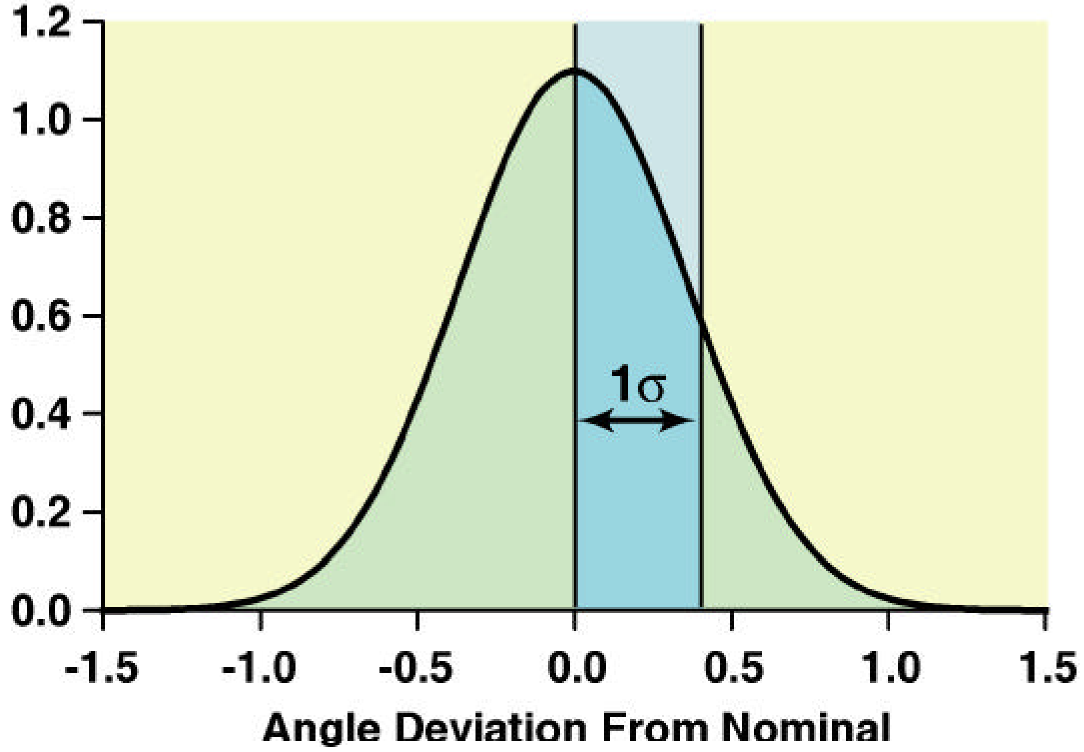


	factor	value	effect1	effect2	effect3	effect4	effect5
32	lvdt	0.014	-0.771	-0.307	-0.432	-0.203	-0.227
15	case_uni_gap	0.01	-0.512	-0.505	-0.504	-0.513	-0.513
6	ang_lev_arm	0.342	-0.316	-0.347	-0.351	-0.347	-0.351
30	pos_aft_mnt_cas	0.002	-0.254	-0.096	-0.133	-0.060	-0.063
14	uni_rad	0.004	-0.223	-0.206	-0.196	-0.203	-0.198
29	pos_mnt_stp	0.0025	-0.156	-0.057	-0.090	-0.038	-0.044
7	vane_profile	0.003	-0.150	-0.159	-0.156	-0.147	-0.149
28	pos_act_stp	0.0025	-0.125	-0.064	-0.086	-0.038	-0.046
1	pos_vn_hl	0.002	-0.093	-0.098	-0.108	-0.100	-0.098
13	pos_uni_hol	0.001	-0.062	-0.050	-0.044	-0.054	-0.049
4	sz_bush_id	0.001	-0.056	-0.050	-0.052	-0.051	-0.053
3	sz_bush_od	0.001	-0.055	-0.058	-0.053	-0.052	-0.051
9	lat_pos	0.0005	-0.047	-0.025	-0.020	-0.025	-0.022
5	sz_vn_stm	0.001	-0.044	-0.058	-0.041	-0.051	-0.051
2	sz_case_hl	0.0005	-0.042	-0.021	-0.017	-0.025	-0.026
21	len_rod	0.004	-0.035	0.004	0.000	0.008	0.006
27	fwd_mnt	0.001	-0.023	0.006	-0.001	0.001	-0.002
12	sz_uni_hol	0.00025	-0.020	-0.012	-0.004	-0.019	-0.013
31	pos_mnt_bell	0.005	-0.017	-0.010	-0.006	-0.008	-0.011
10	sz_hol_brg	0.00025	-0.015	-0.013	-0.020	-0.007	-0.008
11	sz_uni_pin	0.00025	-0.013	-0.010	-0.019	-0.010	-0.008
22	sz_crnk_rod	0.00025	-0.012	0.005	0.011	-0.001	-0.003
17	sz_clv_hol	0.00025	-0.011	0.008	-0.003	0.000	0.002
24	sz_crnk_arm_hol	0.00025	-0.010	0.010	-0.001	-0.003	-0.003
23	con_pin	0.00025	-0.009	0.001	0.001	0.004	0.002
20	sz_uni_rod	0.00025	-0.008	-0.001	-0.002	-0.002	-0.007
16	pos_clevis	0.001	-0.005	0.016	0.027	0.013	0.019
19	sz_clv_pin	0.00025	-0.004	-0.001	0.010	0.002	0.000
25	pos_crnk_arm_hol	0.001	0.007	-0.008	-0.004	0.002	0.003
8	len_sph_brg	0.01	0.009	0.000	0.008	0.000	-0.002
26	srf_bel_crnk	0.004	0.016	-0.005	-0.002	0.001	-0.001
18	pos_clv_hol	0.002	0.018	-0.009	-0.001	-0.001	0.001

Interactions were not important.

Monte Carlo Study Determined the Total Vane Angle Variation

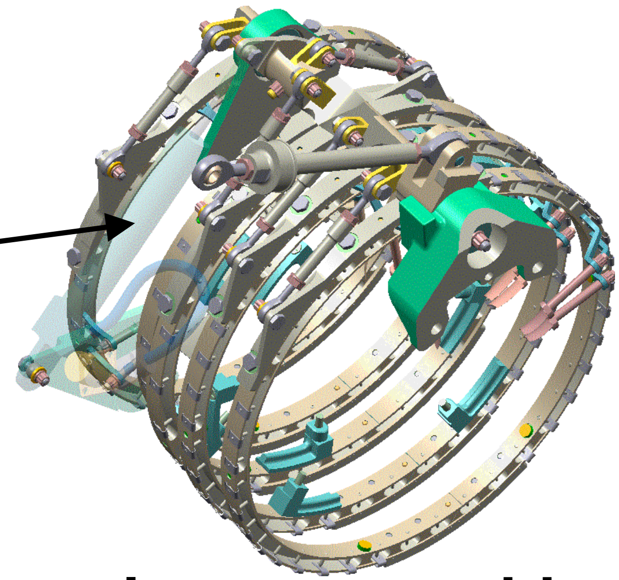
- **Assumed each feature is produce with a 3*s* process**



- **95% are within +/- 0.72 degrees**

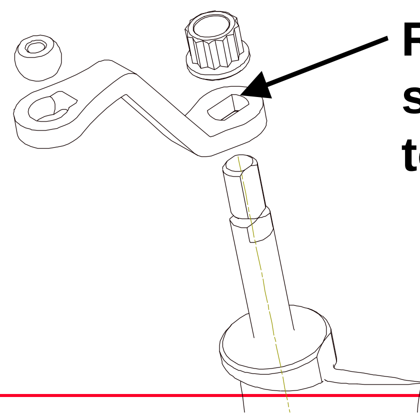
DFSS Resulted in an Improved Design

- LVDT was repositioned to increase sensitivity
  - forward cooler location



New cooler LVDT location increased position sensitivity

- Vane lever arm kept close tolerance at critical location



Required tighter tolerances at the slot end and accepted looser tolerances at the bearing end

DFSS resulted in an improved design

- DFSS resulted in an improved design
- Computer experiments can provide design guidance
- Highly fractionated factorial experiments are a useful way to determine important factors in a design
- DFSS produced a relation

DFSS provides provides a straight forward process to produce.