Experience with Designed Experiments in Aerospace Ground Test: Successes and Challenges

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Introduction

- The history of the use of DOE in aerospace ground testing appears to be rather short
  - Examples
    - NASA LaRC began use in the late 90's
    - USAF AEDC only recently began training in DOE
- Personal experience
  - Began in summer 2001 by setting up wind tunnel experiments for DOE classwork
  - Experience now with DOE use in aerodynamic testing of aircraft, automobiles, trucks as well as instrument calib.
  - Currently teaching DOE/RSM at graduate level to ODU students and conducting industry/gov. training
  - This talk will highlight some of the author's experiences with DOE based problems

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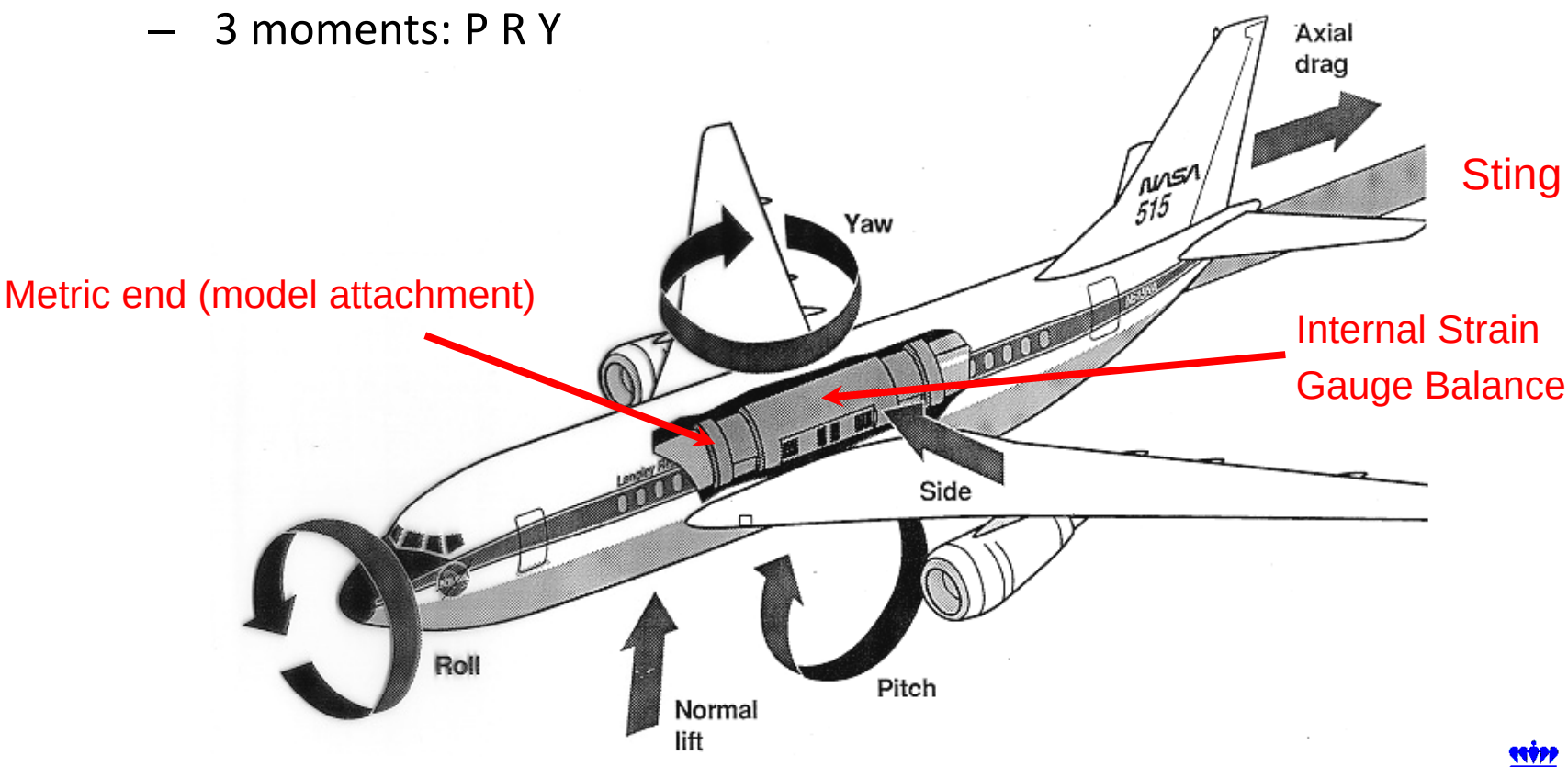
Internal Balance Calibration

- Force and moment measurements are fundamental to wind tunnel testing (two LFST examples below)
- Recently more emphasis on determining uncertainty
- Calibration is required to develop a mathematical model used to predict aerodynamic loading
- Methodology involves an experimental approach executed with a mechanical load system
  - Both manual and automated

Internal Balance Measurements

- Internal balance located in aircraft model
- 6 degrees of freedom, Measures:
  - 3 forces: N A S
  - 3 moments: P R Y



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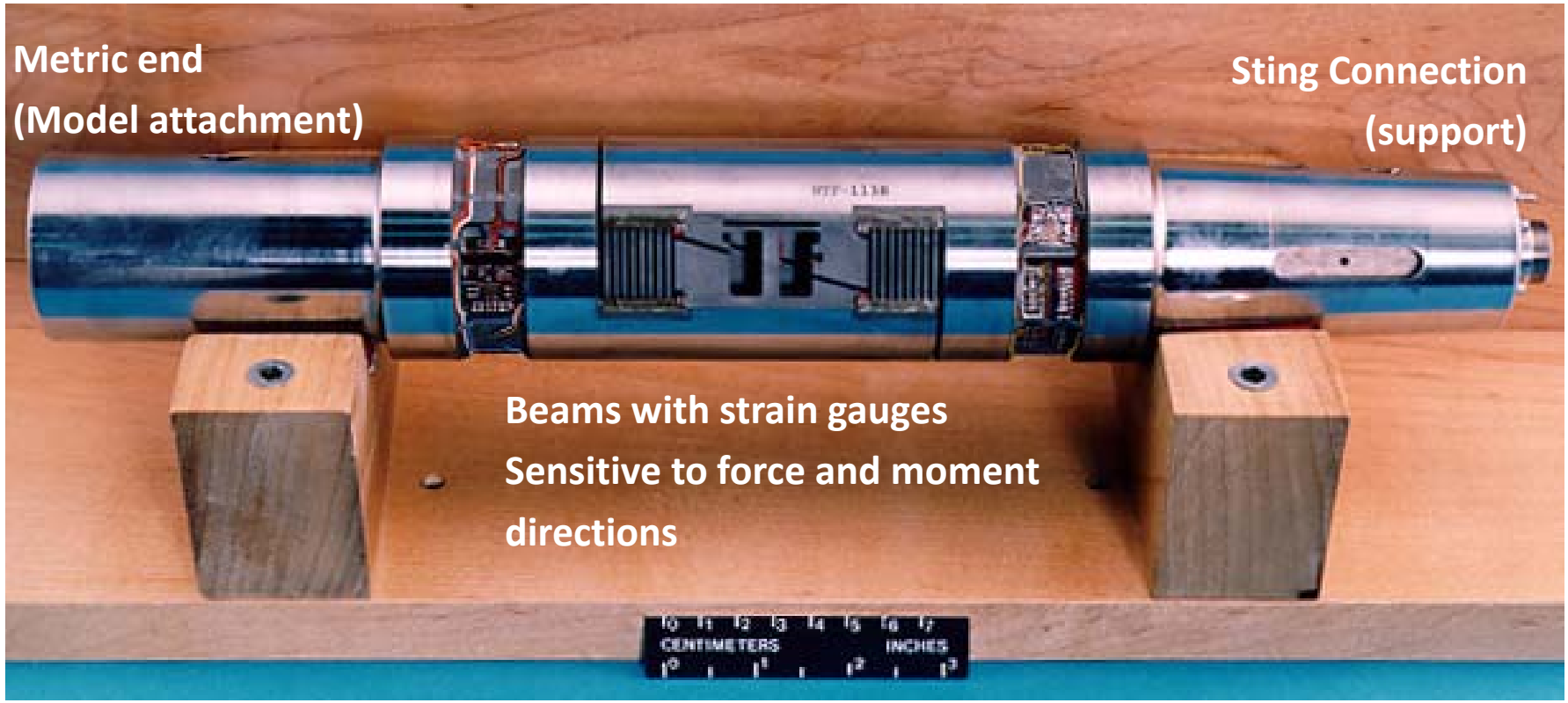
Internal Strain Gauge Balance



Input: Aerodynamic Forces (3) and Moments (3)

Output: 6 Voltages from excited strain gage bridges

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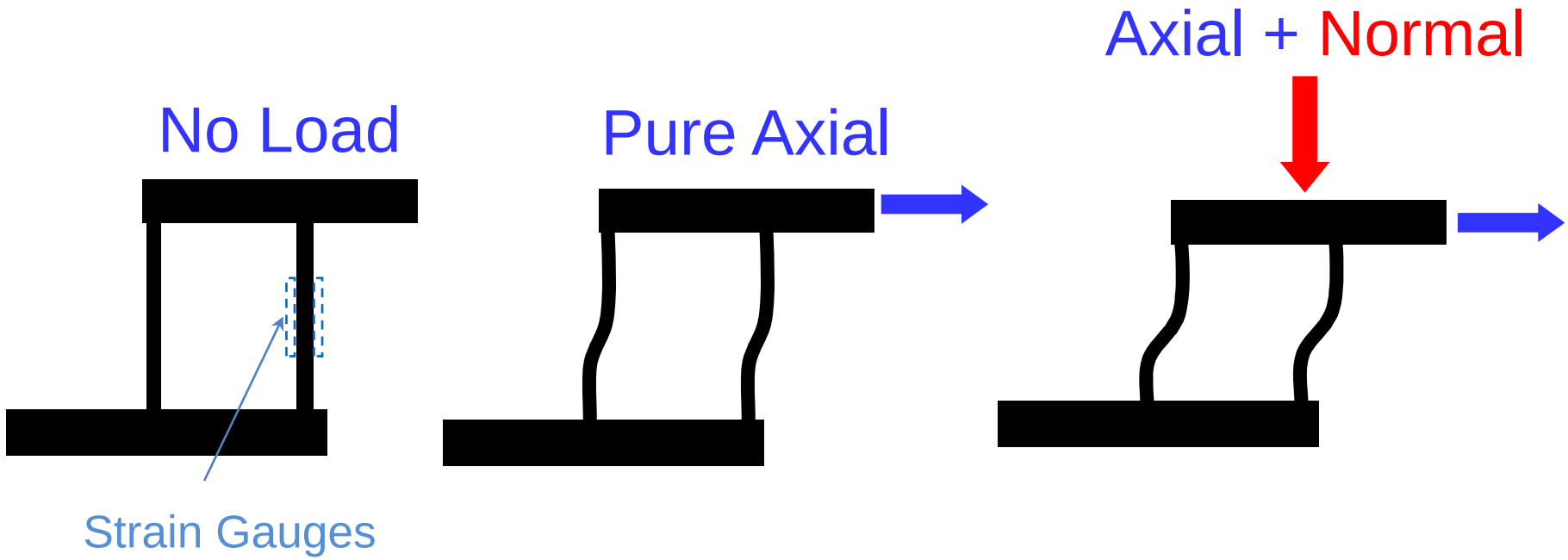
Balance Calibration

- Calibration method
  - Apply known combinations of loadings and collect voltage responses from the balance
  - Build an empirical math model
- No pure loads – interactions will occur
  - Structure design to best characterize interactions
- Historically has been very labor intensive and time consuming

Interactions

- Look at a pair of beams for measuring load in Axial direction but subject to simultaneous loading in Normal direction



- 27 term math model for each component, example of Axial force

$$Axial(volts) = \beta_A A + \beta_N N + \beta_S S + \beta_P P + \beta_R R + \beta_Y Y$$
$$+ \beta_{AN} AN + \beta_{AS} AS \ldots + \beta_{AA} A^2 + \beta_{NN} N^2 + \ldots$$

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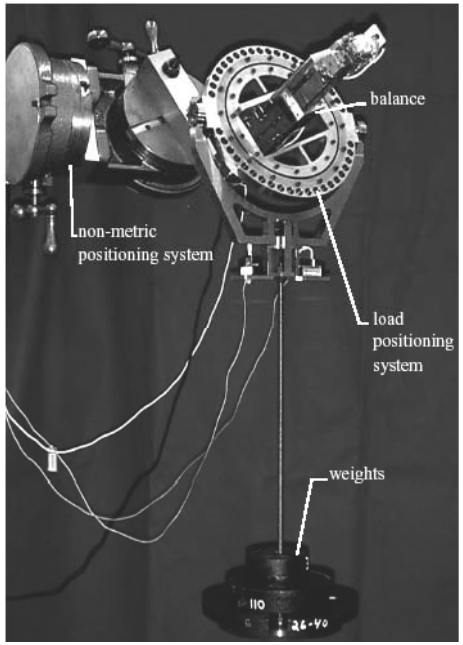
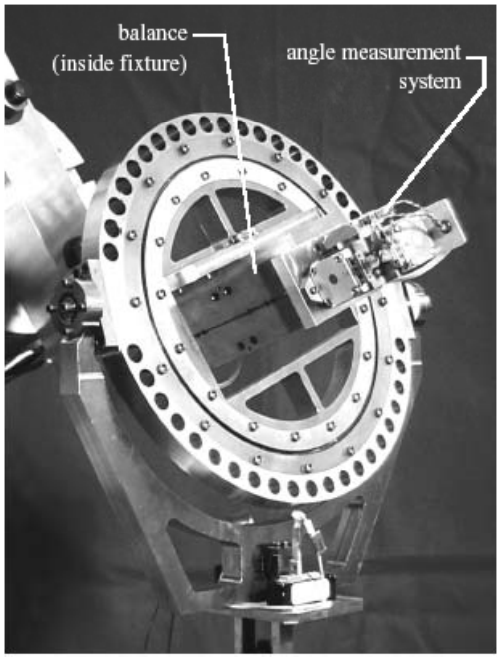
Automated Balance Calibration Example

- NASA LaRC Single Vector System (SVS)
- DOE-based calibration – Central Composite Design
- Automated calibration machine
- Typically 24 hour calibration duration
- Currently limited to balance capacities <u>less than 3000 lbs</u>





Manual Calibration Methods

- Traditionally done with dead weight loading in fixtures with cables and levers to apply loads and moments
- Time consuming – traditional cal takes 3 weeks or more
- Required for high capacity balances

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High-Capacity Balance Calibration Process

- Traditional Experimental Approach
  - Extensive load matrix changing one axis at a time – 729 points
  - Data used to build second order empirical models
  - Proven, accepted method in use for 50 years

- Mechanical Calibration System
  - Reliable, dependable, accurate
  - Heavy loads, slow process
    – 3 to 4 weeks
  - Consider a DOE approach

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Test Matrix Issues

- Which combinations of forces and moments?
  - Ideally, simultaneous loading in all forces and moments for each run (and changing after each) is desired
    - Limitation of manual calibration stand – level of difficulty increases from one to six simultaneous loads
  - The original 729-point uses 5 levels in a pyramid scheme
  - SVS uses 5 levels in modified CCD
  - Quadratic models require only 3 levels
- What about the test sequence?
  - Randomized test sequence is ideal to minimize the effects of unwanted variability on model estimation
  - Increases overall test time due to assembly configuration changeovers

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Chosen Design Approach

- Based on modified Box-Behnken design
- 3 levels hi,mid,low
- Primarily two factors at a time
  - Mechanical constraints force several > 2
- Total of 65 loadings versus traditional 729
- Chose off-center zero run
  - Could be omitted and left as zero loading for further efficiency

Normal	Axial	Pitch	Roll	Yaw	Side	Runs
±1	±1	0	0	0	0	4
±1	0	±1	0	0	0	4
±1	0	0	±1	0	0	4
±1	0	0	0	±1	±1	4
±1	0	0	0	0	±1	4
0.13	±1	±1	0	0	0	4
0.06	±1	0	±1	0	0	4
0	±1	0	0	±1	0.13	4
0	±1	0	0	0	±1	4
0.19	0	±1	±1	0	0	4
0.13	0	±1	0	±1	±1	4
0	0	±1	0	0	±1	4
0	0	0	±1	±1	0.25	4
0	0	0	±1	0	±1	4
0	0	0	0	±1	±1	4
0.10	0	0.10	0.10	0.10	0.10	5

Trial Calibration Summary

- Trial modified BBD took 90 hours (low capacity balance used)
- Traditional 729 OFAT cal on same balance takes 120 hours
  - For a high capacity balance it takes approximately 200-240 hours
  - Time savings should be much more significant with the heavy capacity balance and new method, estimated 40-50% time savings

- In addition, new design has
  - Higher statistical power than traditional design in ability to estimate model terms
  - Robust estimates of uncertainty

- Challenges - Culture
  - Convincing technicians and managers that:
    - Randomization is required
    - 3 levels are enough to define the desired quadratic model

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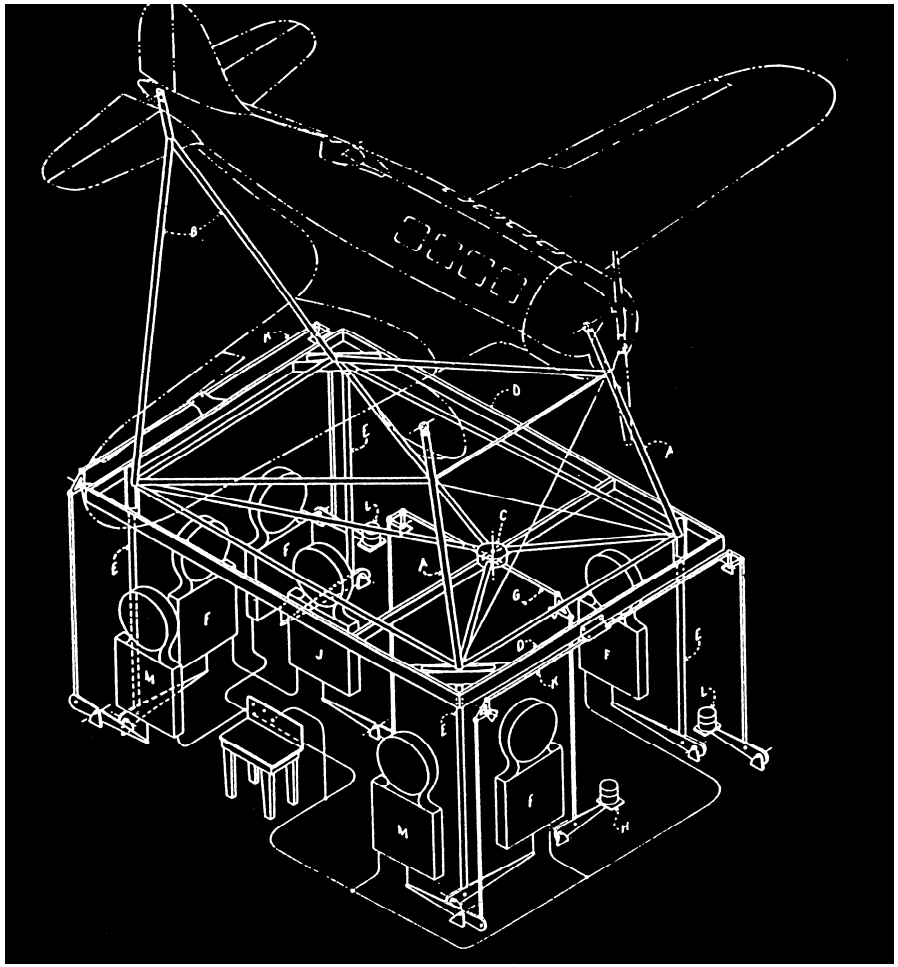
External Balance Calibration

- External balance is *external* to aircraft/ model
- Linkages between model and platform/ platform and scales
- Example from NASA LaRC Full-Scale Tunnel (later called LFST)
- Original engineering drawing form 1930's



Inspiration

- Fall of 2005
  - Minor flooding required rebuilding of FST external balance
  - Boeing Phantom Works hires ODU to test X-48B in spring of 2006
- Fresh calibration required
  - Small differences in link lengths and relative angles as result of refurbishment

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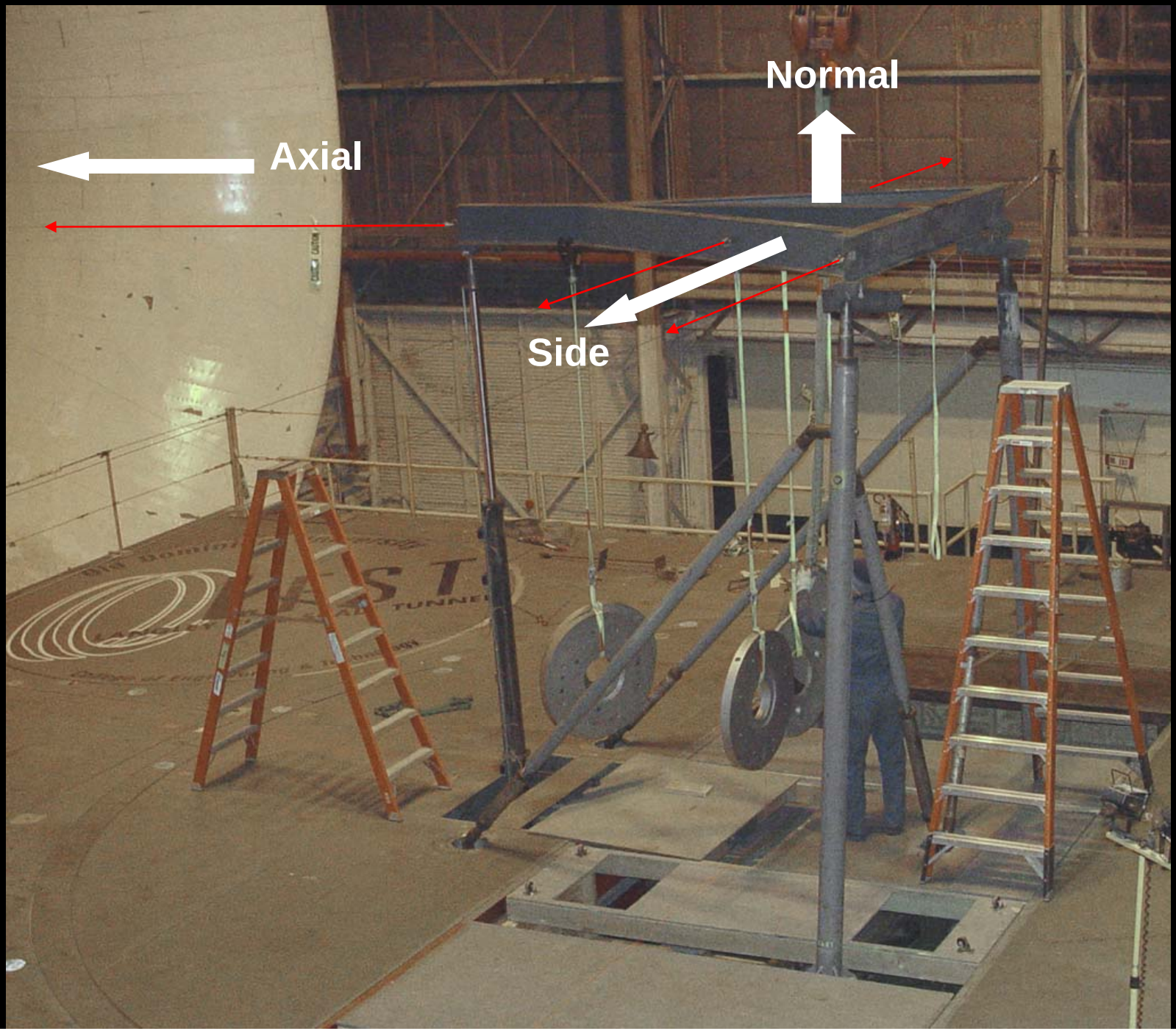
Calibration Approach

- Differs from internal balance
  - Calibration must be done in the facility
    - Desire to minimize downtime of facility
    - No standard loading apparatus (compared to cal. stands)
  - The traditional calibration model is 1st order without interactions
  - Easier to perform multi-component loading (min deflection)
- Common to both approaches, require
  - Sufficient statistical power for model term estimation
  - Robust estimates of uncertainty
  - Minimum number of loadings
  - Provision for interactions
  - Test for model adequacy

Calibration Load Frame

- A rigid frame is positioned on the wind tunnel aircraft support struts to allow multi-component loading
- Weights are hung below to generate pitch & roll moments, normal force
- Cables and pulleys are used to generate side and axial force, yaw moment
- Load frame and cables must be level/orthogonal
  - Usually only have to do this once as compared to internal balance cal where it has to be adjusted for every run

Load Frame



Design Choice

- A 2_{VI}^{6-1} two-level fractional factorial design
  - Run-efficient 32 + centers and validation points
  - Provides minimum desired model order (from past cal)

$$y = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum\sum_{i<j} \beta_{ij} x_i x_j + \varepsilon$$

- Fully randomize the test matrix
  - Protect against lurking vars. e.g. temp
- Load all components simultaneously
  - Run efficient, identifies interactions
- Modifications were required to the ideal design points due to finite load combination limits

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Test Matrix Development

- Sufficient statistical power
  - drives number of runs chosen
- Weigh-beam balance design means relative loadings
  - 0 to 1000 lbs or -500 to +500 same results
- Load ranges chosen
  - Predicted loads on X-48B
  - Availability of weights
  - Distribution of multi-component loadings

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Ideal vs. Achievable

		Ideal Half Fraction						Achievable Factor Levels					
Std Order	Run Order	Normal	Axial	Side	Pitch	Roll	Yaw	Normal	Axial	Side	Pitch	Roll	Yaw
33	1	-500.0	75.0	25.0	1440.0	721.0	177.7	-500.4	80.0	30.0	2312.9	721.0	123.3
10	2	0.0	0.0	0.0	3400.0	1.5	-4.6	0.0	0.0	0.0	3234.5	1.5	0.0
36	3	-500.0	75.0	25.0	1440.0	721.0	177.7	-500.4	80.0	30.0	2312.9	721.0	123.3
15	4	-1000.0	150.0	50.0	3400.0	1.5	360.0	-1000.9	150.0	50.0	3496.2	443.8	358.0
20	5	0.0	150.0	0.0	-513.3	1229.0	360.0	0.0	150.0	0.0	29.2	1.5	302.6
35	6	-500.0	75.0	25.0	1440.0	721.0	177.7	-500.4	80.0	30.0	2312.9	721.0	123.3
30	7	0.0	0.0	50.0	3400.0	1229.0	-4.6	0.0	0.0	50.0	3234.5	1229.0	55.5
4	8	0.0	150.0	0.0	-513.3	1.5	-4.6	0.0	150.0	0.0	29.2	1.5	-4.6
17	9	-1000.0	0.0	0.0	-513.3	1229.0	360.0	-1000.9	0.0	0.0	-227.0	1086.9	307.2
25	10	-1000.0	0.0	0.0	3400.0	1229.0	-4.6	-1000.9	0.0	0.0	2082.5	1088.4	0.0
34	11	-500.0	75.0	25.0	1440.0	721.0	177.7	-500.4	80.0	30.0	2312.9	721.0	123.3
9	12	-1000.0	0.0	0.0	3400.0	1.5	360.0	-1000.9	0.0	0.0	2857.5	-31.0	307.2
22	13	0.0	0.0	50.0	-513.3	1229.0	360.0	0.0	0.0	50.0	0.0	1227.5	362.7
16	14	0.0	150.0	50.0	3400.0	1.5	-4.6	0.0	150.0	50.0	3860.5	102.9	50.8
23	15	-1000.0	150.0	50.0	-513.3	1229.0	360.0	-1000.9	150.0	50.0	-513.3	1193.9	358.0
31	16	-1000.0	150.0	50.0	3400.0	1229.0	-4.6	-1000.9	150.0	50.0	3455.3	1196.4	50.8
29	17	-1000.0	0.0	50.0	3400.0	1229.0	360.0	-1000.9	0.0	50.0	2870.2	1197.9	362.7
5	18	-1000.0	0.0	50.0	-513.3	1.5	360.0	-1000.9	0.0	50.0	-227.0	77.0	362.7
7	19	-1000.0	150.0	50.0	-513.3	1.5	-4.6	-1000.9	150.0	50.0	-513.3	76.0	50.8
26	20	0.0	0.0	0.0	3400.0	1229.0	360.0	0.0	0.0	0.0	3234.5	1119.5	307.2
28	21	0.0	150.0	0.0	3400.0	1229.0	-4.6	0.0	150.0	0.0	3072.8	1119.5	-4.6
21	22	-1000.0	0.0	50.0	-513.3	1229.0	-4.6	-1000.9	0.0	50.0	-227.0	1194.9	55.5
3	23	-1000.0	150.0	0.0	-513.3	1.5	360.0	-1000.9	150.0	0.0	-513.3	-31.0	302.6
6	24	0.0	0.0	50.0	-513.3	1.5	-4.6	0.0	0.0	50.0	0.0	109.5	55.5
14	25	0.0	0.0	50.0	3400.0	1.5	360.0	0.0	0.0	50.0	3234.5	109.5	362.7
12	26	0.0	150.0	0.0	3400.0	1.5	360.0	0.0	150.0	0.0	3682.4	0.0	302.6
24	27	0.0	150.0	50.0	-513.3	1229.0	-4.6	0.0	150.0	50.0	29.2	1226.4	50.8
1	28	-1000.0	0.0	0.0	-513.3	1.5	-4.6	-1000.9	0.0	0.0	-227.0	-32.5	0.0
2	29	0.0	0.0	0.0	-513.3	1.5	360.0	0.0	0.0	0.0	0.0	0.0	307.2
11	30	-1000.0	150.0	0.0	3400.0	1.5	-4.6	-1000.9	150.0	0.0	3455.3	-32.5	-4.6
32	31	0.0	150.0	50.0	3400.0	1229.0	360.0	0.0	150.0	50.0	3072.8	1229.0	358.0
13	32	-1000.0	0.0	50.0	3400.0	1.5	-4.6	-1000.9	0.0	50.0	3467.0	78.5	55.5
19	33	-1000.0	150.0	0.0	-513.3	1229.0	-4.6	-1000.9	150.0	0.0	-513.3	1088.4	-4.6
18	34	0.0	0.0	0.0	-513.3	1229.0	-4.6	0.0	0.0	0.0	0.0	1119.5	0.0
27	35	-1000.0	150.0	0.0	3400.0	1229.0	360.0	-1000.9	150.0	0.0	3455.3	1086.9	302.6
8	36	0.0	150.0	50.0	-513.3	1.5	360.0	0.0	150.0	50.0	29.2	102.9	358.0

Minor Effects on Chosen Model

- Power is only slightly effected at the desired 2 std dev level
  - ME's 99.9 vs. low 96.1
  - 2FI's 99.9 vs. one low of 87
- VIF evaluates multicolinearity
  - R.O.T desire <10
  - 1.18 is the worst case here

		Power at α = 5%	
Term	**VIF**	**1 Std. Dev.**	**2 Std. Dev.**
A	1.05	70.9 %	99.9 %
B	1.08	69.7 %	99.9 %
C	1.07	70.5 %	99.9 %
D	1.15	46.3 %	96.1 %
E	1.11	56.6 %	98.9 %
F	1.09	55.6 %	98.7 %
AB	1.08	69.9 %	99.9 %
AC	1.09	69.3 %	99.8 %
AD	1.11	47.0 %	96.4 %
AE	1.10	56.8 %	98.9 %
AF	1.08	55.5 %	98.7 %
BC	1.07	70.1 %	99.9 %
BD	1.11	46.5 %	96.2 %
BE	1.14	55.3 %	98.6 %
BF	1.10	54.5 %	98.5 %
CD	1.07	48.1 %	96.8 %
CE	1.06	57.8 %	99.0 %
CF	1.05	55.8 %	98.7 %
DE	1.18	35.1 %	88.1 %
DF	1.14	34.0 %	87.0 %
EF	1.14	42.6 %	94.2 %

Calibration Summary

- Successes
  - 32 factorial runs + 4 centers + 5 validation points = 41 total loadings
    - Passed test for lack of fit
    - If a higher order model is required, easy to augment to CCD
    - Future calibrations or check cals could use 2_{IV}^{6-2} as only a few 2FI's found
  - Minor changes in set points from standard design had negligible impact on model quality
  - 13 hours vs. 40 hours of previous OFAT calibration
  - Robust validation of first order + 2 FI model and uncertainty level estimation
  - A successful test of the X-48B and later X-48C followed the calibration

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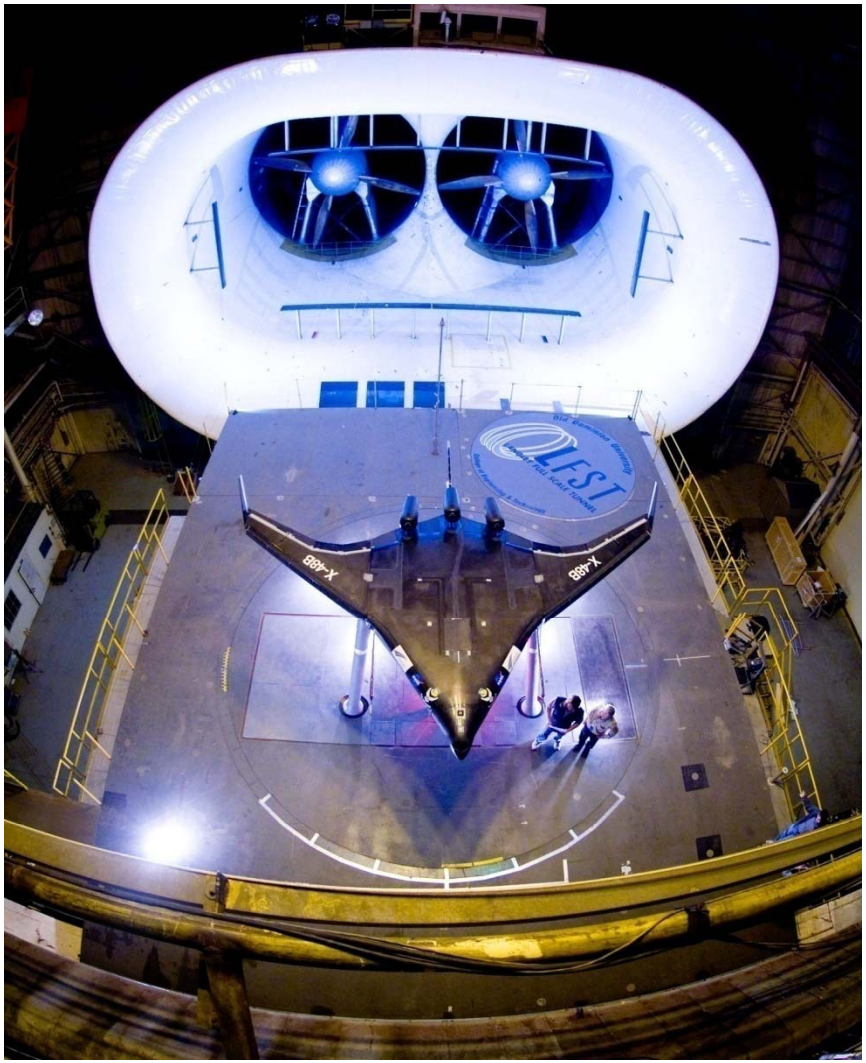
Calibration Summary

- Challenges – Mostly Cultural
  - Simultaneous multi-component loading requires that more weights be available versus previous OFAT design
  - Engineers have traditionally felt that a load sequence involving 5 or more levels is required
    - to characterize an essentially first order system ?
  - Technicians have to be taught to accept the fully randomized test sequence
    - Always a struggle as they think they are “doing it the hard way”

Background: Blended Wing Body at the LFST

Year long test program 2005-2006
- NASA Static model testing
- NASA Free flight model testing
- Boeing X-48 B flight model

3 Month Program in 2009
- Boeing X-48 C flight model



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Typical Low-Speed Wind Tunnel Test Objectives

- Aerodynamic Characterization
  - A math model describing each response in terms of all the factors i.e. $C_D=C_D(\alpha,\beta,\delta_1, \delta_2,\ldots)$
    - Stability and Control analysis
    - Computer flight simulations
  - Limits to flight (eg. stall)
- Capture the true uncertainty in testing
  - The sum of error due to:
    - Setting the control surfaces
    - Setting attitude
    - Force balance variances
    - Dynamic pressure measurement
    - Environmental effects

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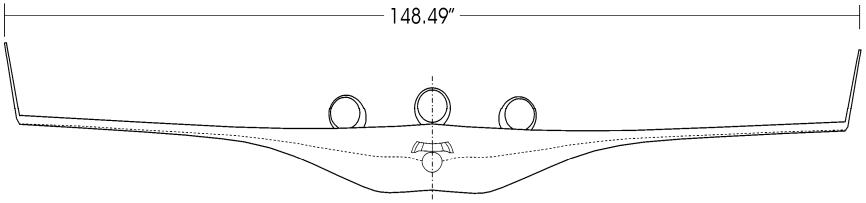
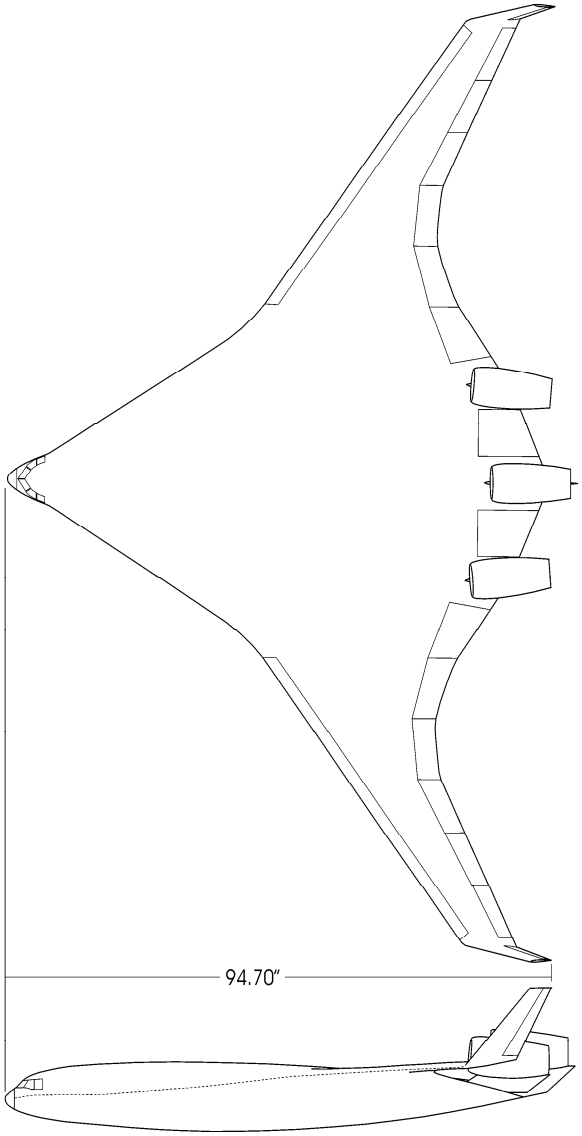
Low Speed Wind Tunnel Testing

- DOE methods are a natural fit for aerodynamic characterization
  - Typically large number of factors involved
    - Control surface deflections (at least 3-5 typically)
    - Attitude – 2 factors, sideslip and angle of attack
    - Power effects – thrust simulation
    - Landing gear up/down
    - Configuration changes (eg. Slat A or B)
  - Use of actuated control surfaces helps accommodate randomization
    - Loads at relatively low dynamic pressure will allow

BWB Case Study

- Potential Factors
  - 18 trailing edge mounted elevons
  - 3 pylon mounted engines with thrust simulation
  - 2 Leading edge slats
  - 2 Winglet rudders





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5% Scale Static Testing at the LFST

- Objectives
  - Aerodynamic characterization including
    - Static stability
    - Control power
- Sting supported
- Internal Balance
- Remotely actuated surfaces
- Air ejectors for thrust

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Stability and Control Test

- A subset of controls were chosen
  - Due to actual model limitations of ganged surfaces
  - Due to limited resources for the DOE test
- Look at response due to left wing control surfaces
  - Use full range of surface deflections
  - Look at one right wing surface
- Interested in possible interactions with adjacent surfaces
- Angle of attack chosen to bracket cruise conditions (angular orientation in vertical plane)
- Small sideslip range (angular orientation in horizontal plane)

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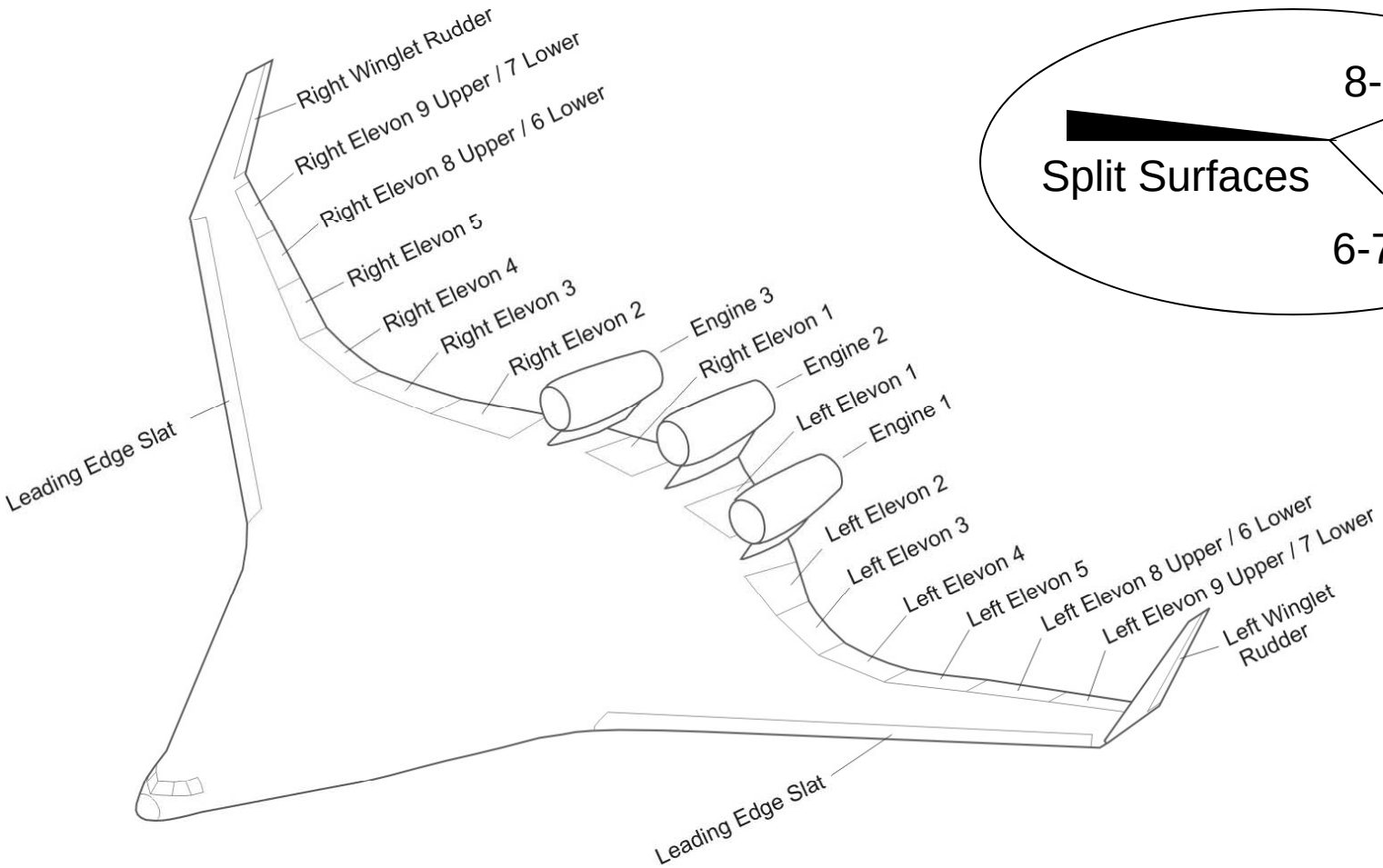
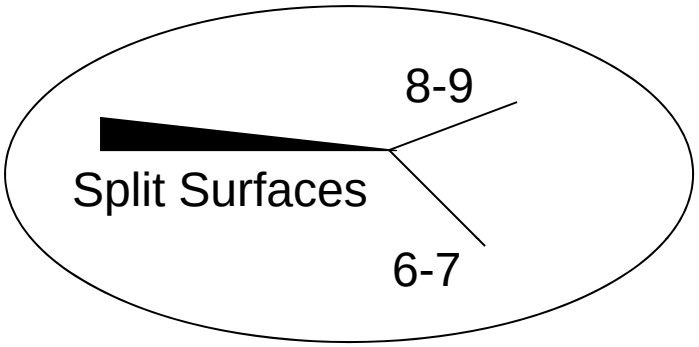
BWB Model Control Surfaces





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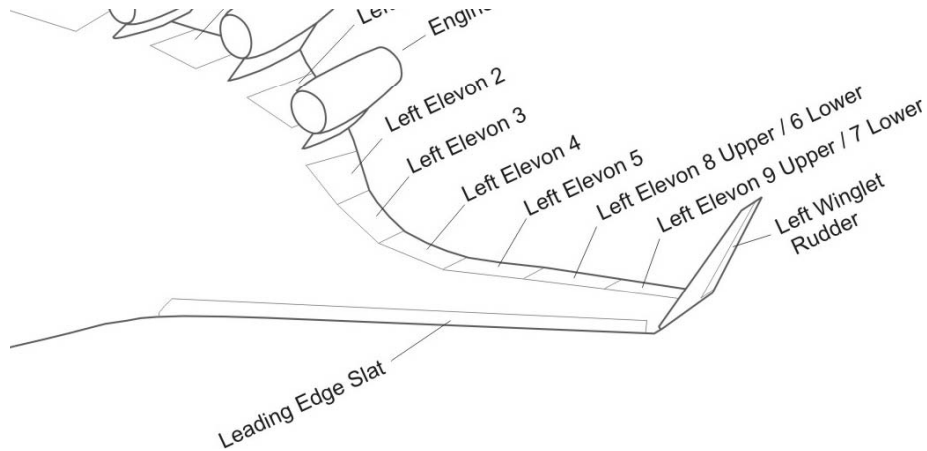
8 Factors Chosen



All are given in degrees

Factor	Factor ID	Low	Center	High	Constraints
α	A	4	7	10	none
β	B	-5	0	5	none
δ_{R25}	C	-30	-5	20	none
δ_{1}	D	-30	-5	20	none
δ_{L25}	E	-30	-5	20	none
δ_{L67}	F	-30	10	50	F - G > 5
δ_{L89}	G	-50	-15	20	F - G > 5
δ_{Lrud}	H	-20	5	30	none

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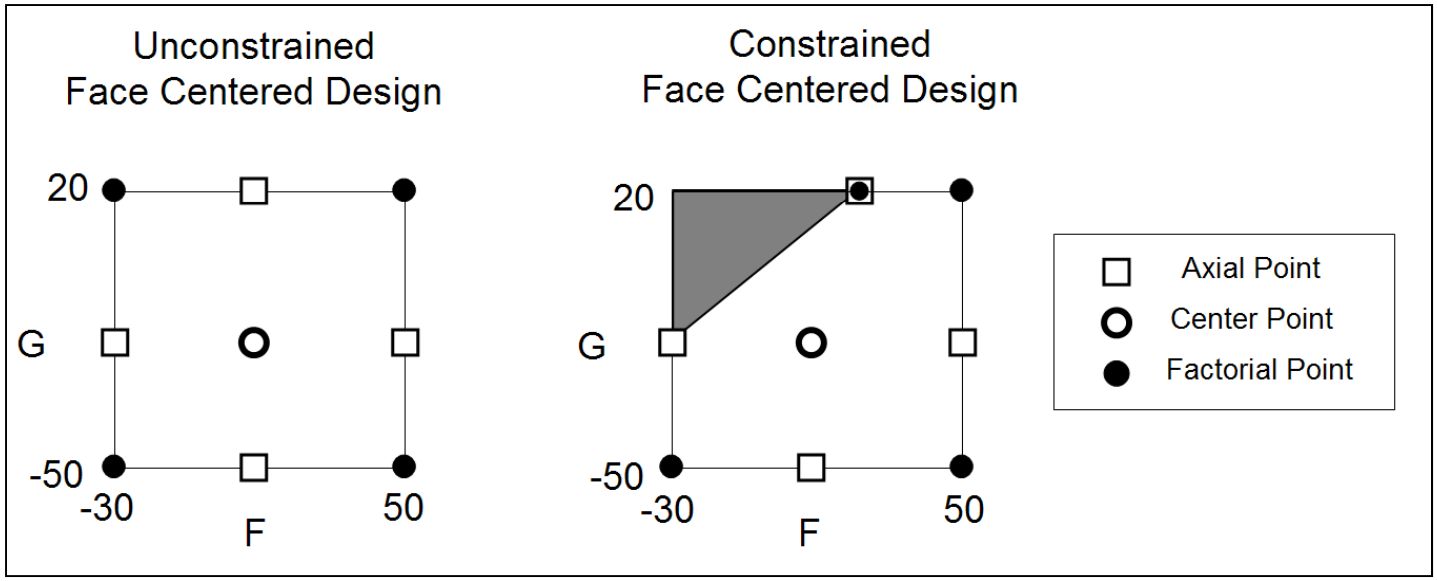
BWB DOE Design Criteria

- Allow at least 3 levels for control surface set points
- Robust to control surface set point error
- Model order for force and moment responses
  - Pure quadratics, possible 2 F.I.'s and 3 F.I.'s
  - Can sequentially augment design by adding design points to build higher order model if required
- Design must accommodate constraints, modified CCD used



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Experiment Details

- Fully automated test
  - Control surfaces actuated
  - Attitude control programmed
- Fully randomized test matrix
- Use 2 Blocks
  - Day 1: ½ Fraction factorial and ½ of center points
  - Day 2: Axials and remaining center points
  - Blocks to protect against “nuisance factors”

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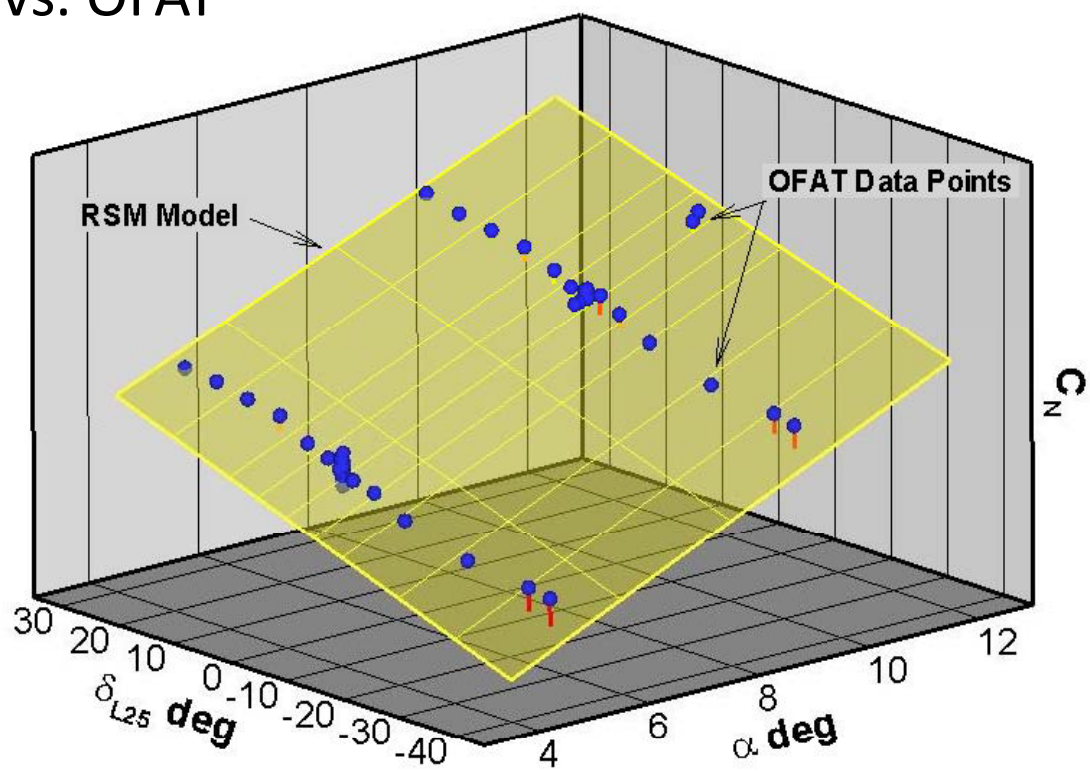
Results: Comparison to OFAT

- Example: Left Ganged Elevons 2-5 versus angle of attack, response is Normal force
- Half the data volume vs. OFAT
- Statistically justified uncertainty estimates
- Regression model as function of all factors
- All potential Interactions modeled



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Optimization

- Complex control surface configurations present an interesting opportunity in that choices arise in allocation of surfaces to achieve specific control objectives
- DOE regression models include effects of all control surfaces and interactions – a natural for optimization
- Example (using Desirability approach)
  - Using any combination of control surfaces tested
  - Find <u>maximum yaw moment magnitude</u> with <u>minimum roll magnitude</u>

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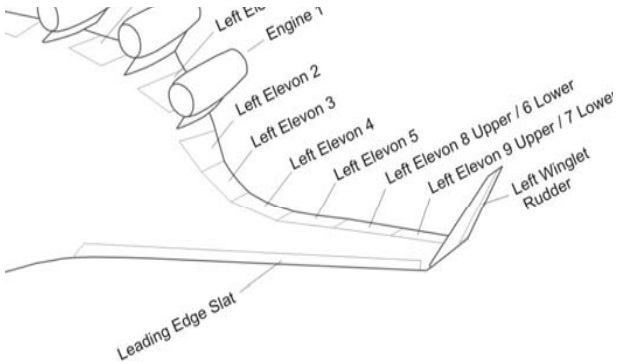
Example: Max Yaw for Min Roll

- Results show elevons 6-7 down and 8-9 up at the optimum, winglet rudder full deflection with 2-5 used to “trim”
- Roll moment (C_l) was nearly zero with yaw moment (C_n) 90 % of maximum



Solution	δ_{L25}	δ_{L67}	δ_{L89}	δ_{Lrud}	$C_{n\ (\%\ Best)}$	$C_l/C_{n\ (\%)}$	Desirability
1	-6.44	40.00	-33.98	30.00	90.11	0.842	0.823
2	-11.54	40.00	-35.85	30.00	100.00	80.686	0.806
3	-10.10	40.00	-13.39	29.93	73.61	0.000	0.789
4	2.69	-26.45	-35.83	30.00	71.63	0.001	0.785
5	2.50	-25.08	-35.85	29.97	70.61	0.188	0.783
6	-3.22	17.80	-35.85	30.00	69.77	-0.003	0.781
7	1.45	-17.31	-35.85	29.88	65.91	-0.003	0.773

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Summary

- Regression models developed for all aerodynamic forces and moments as a function of 8 factors
- Uncertainty estimates including effects of exercising all factors
  - Researchers initially felt these estimates were high after comparing to OFAT estimates
  - Residual analysis revealed problems with actuated surfaces reaching set points that were undiagnosed in preceding 2-week long OFAT investigation
- Identification of interactions on new configuration
- Optimization opportunities

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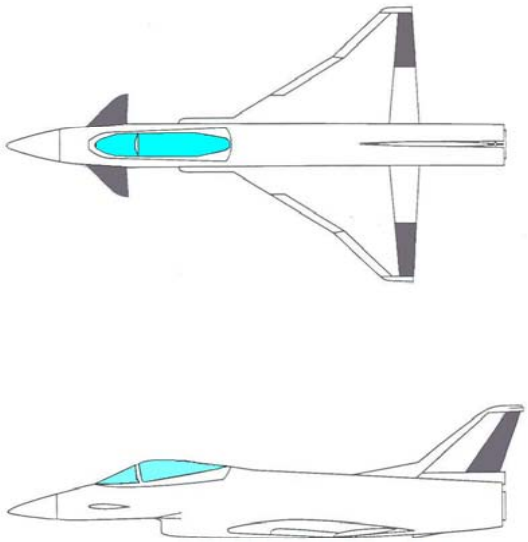
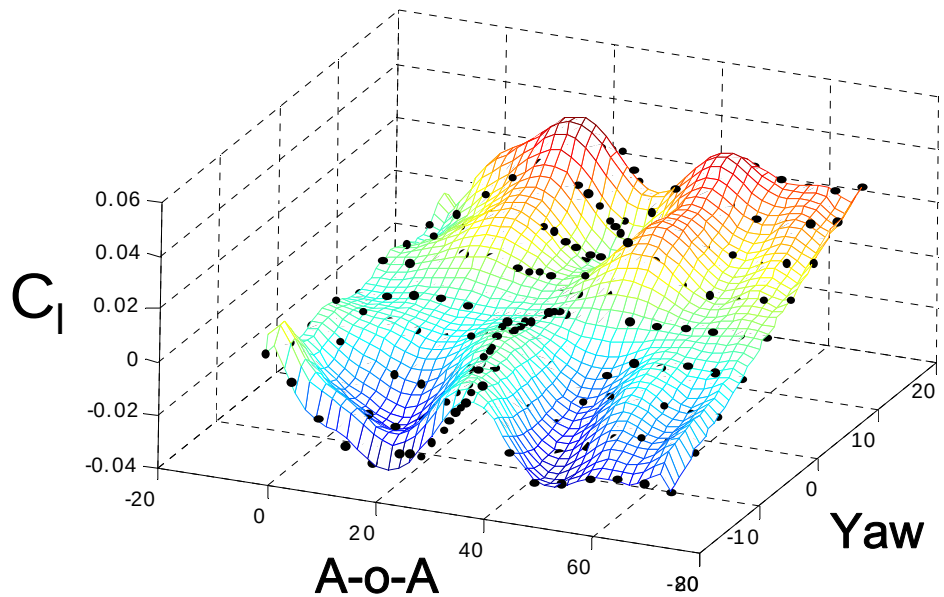
Low Speed Wind Tunnel Test Challenges: Highly Non-Linear Regions

- How to model with low order polynomials
  - Rolling moment of X-31 high-performance aircraft example





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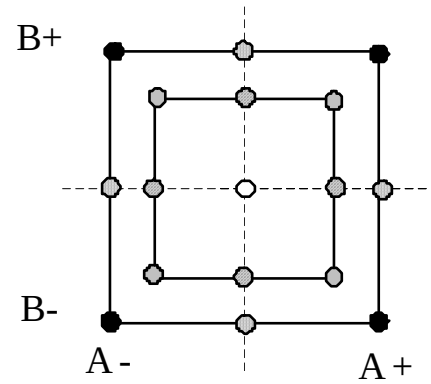
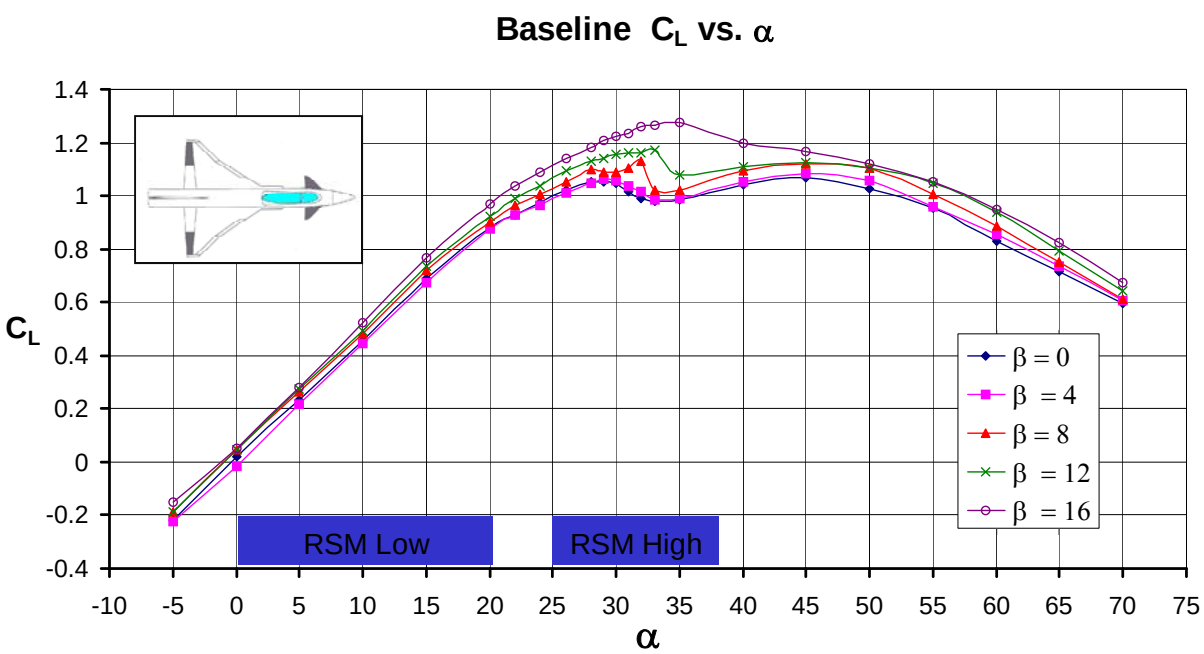
Highly Non-Linear Regions

- Exploratory study required
- Higher order hybrid designs valuable
- Design space may be broken into subspaces
  - Issue often cited is how to handle adjacent spaces at the borders
    - Fairing functions
    - Final use is typically lookup tables



Nested FCD Hybrid



LSWT Challenges: Hard-To-Change Factors

- Factor choices that require replacement of parts may be impractical for a fully randomized design
  - One solution is to run a split-plot design, introduces multiple error sources
  - Analysis is complicated but now supported by commercial software
- Example MAV, wingtip height is hard-to-change (a whole plot factor), A-o-A and Yaw are easy to change (subplot factors)

Standard Order	*Run Order*	*Wingtip Height*	*AoA*	*Yaw Angle*
20	1	3	6	0
17	2	3	14	0
19	3	3	6	10
16	4	3	-2	0
18	5	3	6	-10
14	6	4	14	10
12	7	4	-2	10
11	8	4	-2	-10
15	9	4	6	0
13	10	4	14	-10
2	11	2	-2	10
1	12	2	-2	-10
3	13	2	14	-10
5	14	2	6	0
4	15	2	14	10
10	16	3	6	0
9	17	3	6	10
6	18	3	-2	0
8	19	3	6	-10
7	20	3	14	0

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High Speed Wind Tunnel Testing Challenges

- Traditional DOE methods rely on randomization, difficult for:
  - Factors of Reynolds and Mach number
    - Resource intensive to randomly set combinations
  - Control surface deflections as factors
    - Loads are often too high to use actuators
    - fixed brackets are common (and make for hard to change factors)
  - Factors sideslip and angle of attack
    - Often possible to automate
- Again, one solution is a split plot design structure

Challenge: Training

- How do we train the engineering staff in use of DOE ?
  - Experience with training at AEDC
    - Culture change - observations
      - It's a steep learning curve for those that have never studied statistics or regression
      - Focus has historically been on rapid acquisition of high precision data - **not** empirical model adequacy/quality
      - Sequential experimentation is often viewed as unnecessary
      - Fractional factorials felt to leave too much up to chance
    - Aversion to randomization
      - Many hard to change factors in AEDC facilities works against easy adoption of DOE
      - Reliable, low noise experimental facilities often breed cavalier attitudes: "Protect against what lurking variable – we don't have those"

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