THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Improved Test and Evaluation of Prototypes Using Designed Experiments

International Test and Evaluation Association

20th Test Instrumentation Workshop - Las Vegas, NV

May 11, 2016

Paul Fiorenza, Timothy Blackburn, PhD, Andreas Garstenauer, PhD

Dissertation Research Topic

Department of Engineering Management and Systems Engineering

School of Engineering and Applied Science

The George Washington University

This research is in partial fulfillment of the requirements for the Doctor of Philosophy degree at The George Washington University

Introduction

- Increasing application of Design of Experiments across DoD Test and Evaluation
  - ~ 2000: 53 TW & 46 TW
  - 2009: DOT&E and DT&E emphasis
  - 2012: STAT T&E Center of Excellence
  - Jan 2015: DoDI 5000.02 STAT/DoE formalized as part of T&E
  - Aug 2015: Air Force Test Center – Defensible Test and Evaluation Guidance

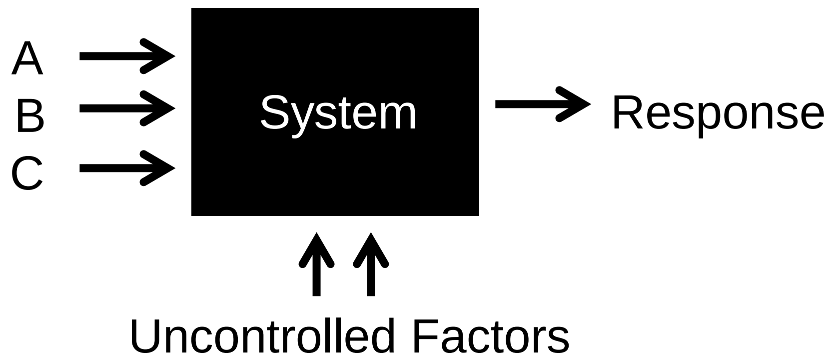
- DoE enables maximum information from limited data
  - Utilizes Replication, Randomization

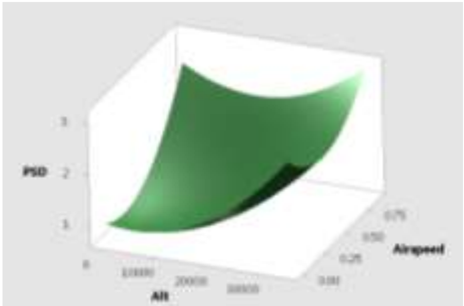
- Barriers to acceptance by Experimental & Developmental test community
  - Culture – long history of OFAT
  - Limited applications requiring experimentation approach
  - Expertise gap – statistics vs. engineering

- Attributes of Developmental Test prototypes
  - High fidelity models
  - Expensive

Question: What experimental designs are efficient for testing prototypes when randomization of data is not desired?

Designed Experiments





- Factors (A,B,C) & Levels (+1,0,-1)
- Response = $X_0 + X_1A + X_2B + X_3C + X_4AB + X_5AC + X_6BC$
- Analysis of Variance (ANOVA) identifies multi-factor interactions

- Randomization – washes out nuisance variables
- Replication – enables statistical power
- Disciplined experimentation approach yielding system information <u>efficiently</u>

Applications to Prototype T&E

- Developmental Test utilized for physical prototypes
  - Mature mechanistic system model exists
  - Controlled testing environment
  - "Black Box" experimentation not required
  - DT&E focuses on system performance or specification verification

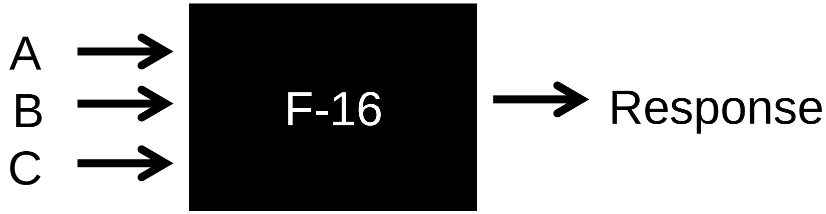
- OFAT historical approach
  - Subject matter expert designed
  - Focus on edge of envelope cases
  - Attempt to identify non linear effects & discontinuities
  - Enables "build-up" from "heart" of envelope
  - Safety & Efficiency

- DoE Examples
  - 2010 - F-16 vibratory load: 16 – 33% of data points vs. OFAT
  - 2015 - AEDC 4T wind tunnel calibration
    - 76 % of data points / <u>1.6 X cost</u>

- Less points yet higher cost?

Example Test Design

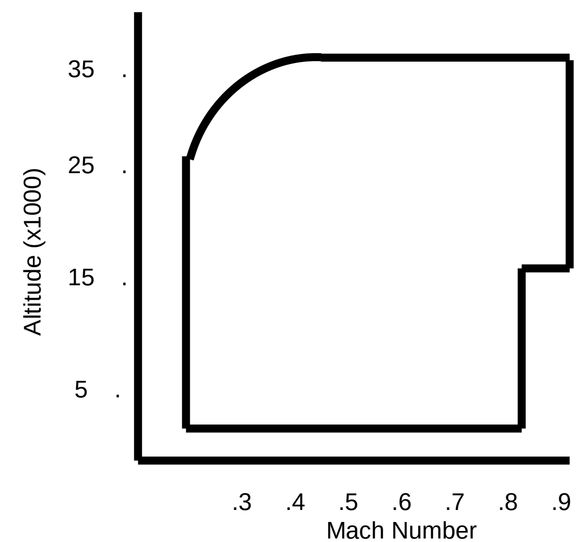
Effect of targeting pod installation on vibratory loads of F-16 aircraft



Response = Vibratory load (Power Spectral Density**)**

1) Select Factors:
   - Altitude
   - Airspeed
   - Angle of Attack

2) Select Levels
   - Altitude (feet): 5000, 15000, 25000, 35000
   - Airspeed (Mach): .3 , .5 , .7 , .9
   - Angle of Attack (deg): 0, +3



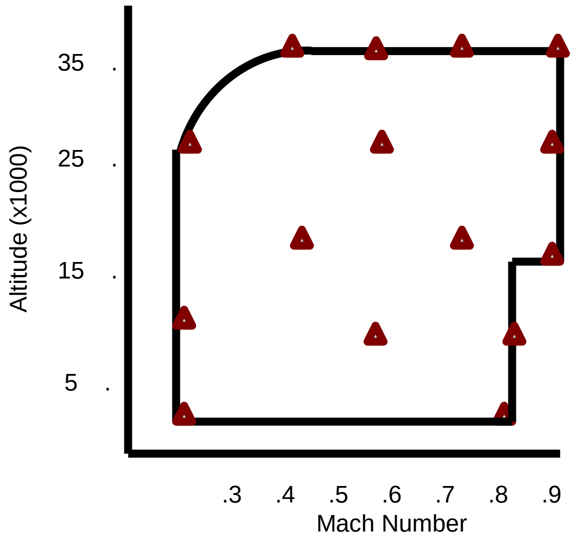
Tucker, A.A., Hutto, G.T, Dagli, C.H. (2010) Application of Design of Experiments to Flight Test: A Case Study, Journal of Aircraft,

One Factor At a Time vs. DoE

Effect of targeting pod installation on vibratory loads of F-16 aircraft

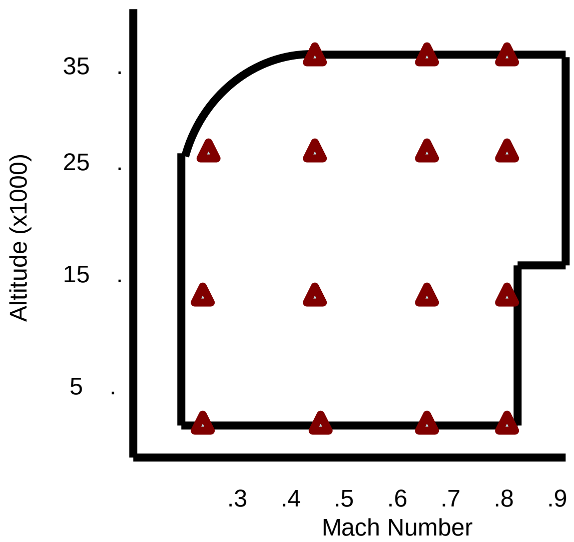
- **Factors: Altitude, Airspeed, Angle of Attack**
- **Response: Power Spectral Density of vibratory load**

One Factor At a Time - Design



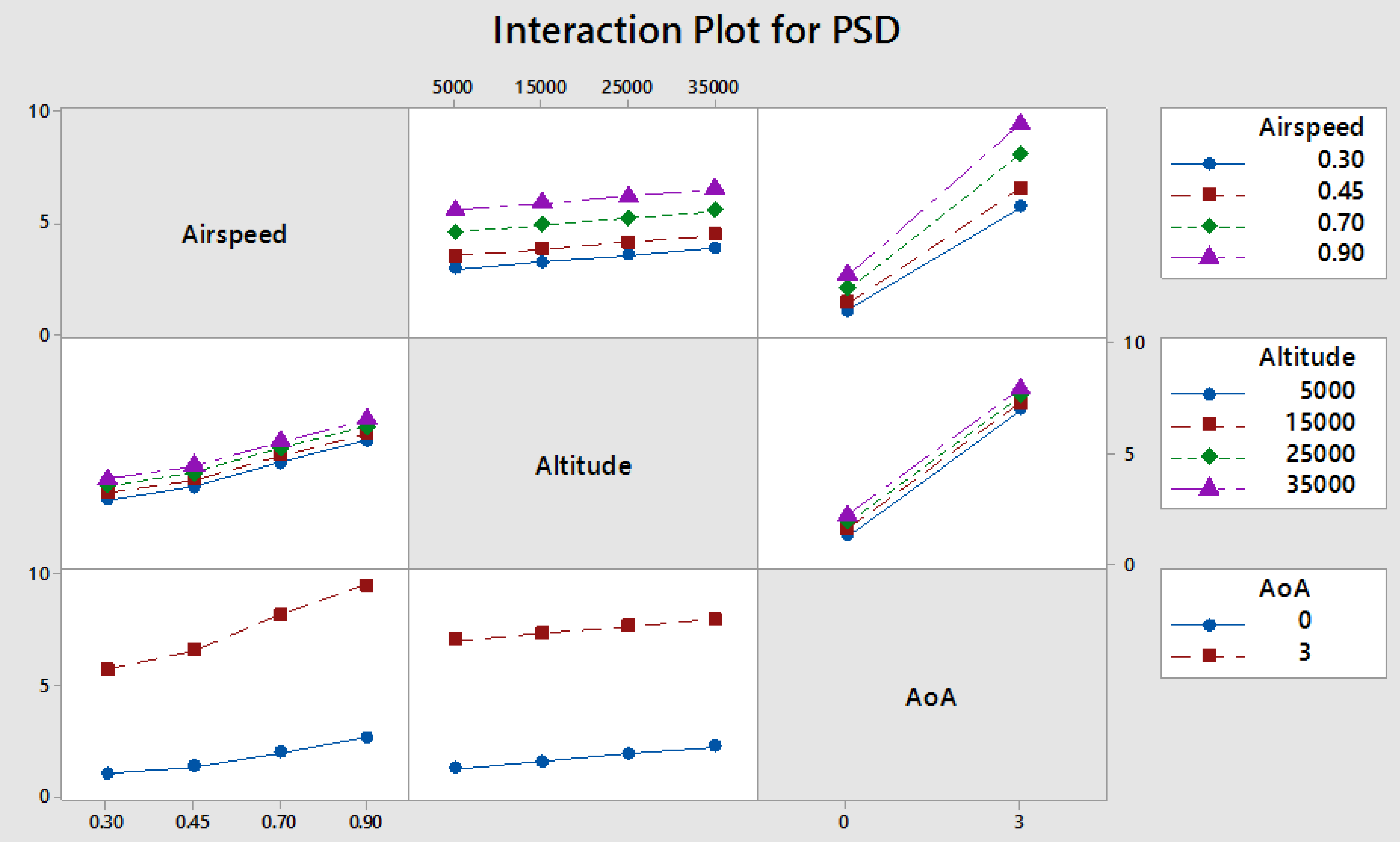
- **Subject Matter expert designed**
- **Predictive model shows areas of emphasis**
- **Focuses on "Edge of Envelope"**
- **15 locations x 2 AoA levels = 30 points**

Full Factorial - Design



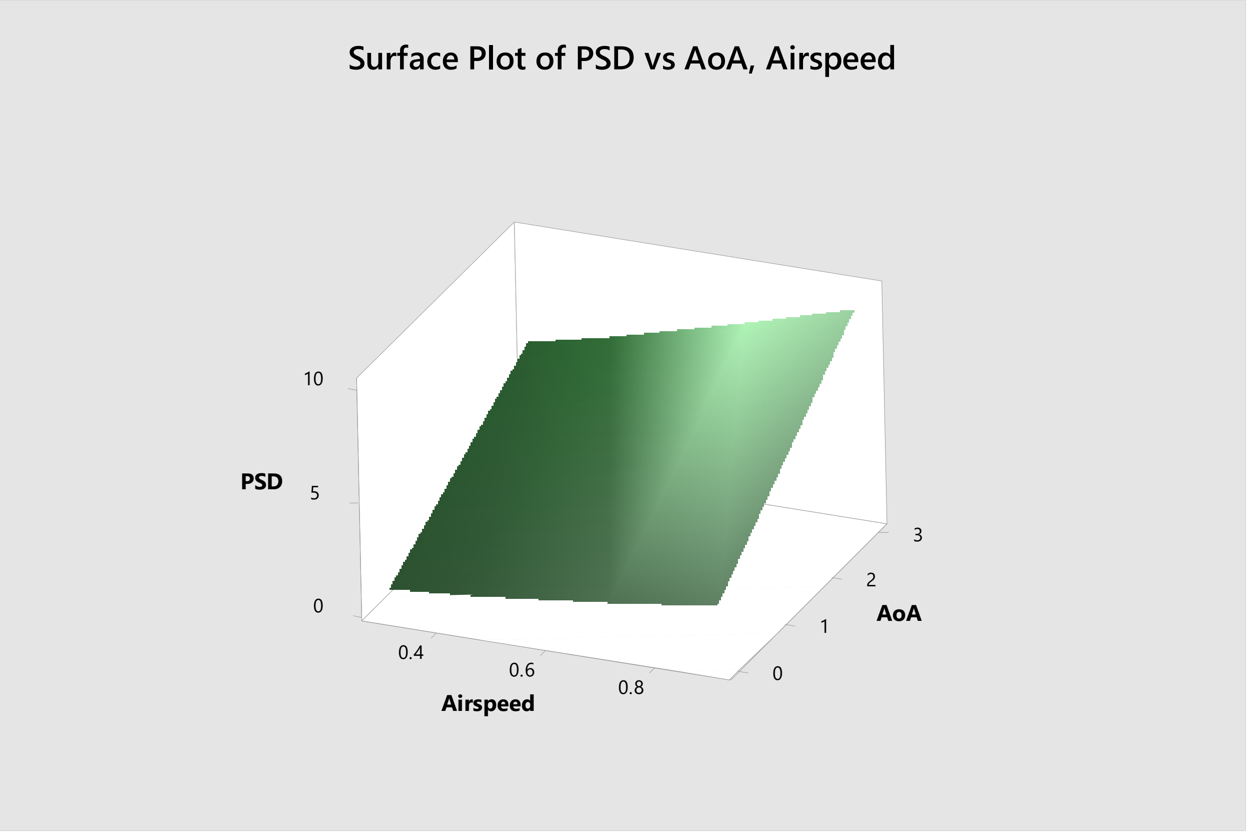
- **Altitude & Airspeed – 4 levels**
- **AoA – 2 levels**
- **N=4^k * 2 = 32**

Multifactor Interactions



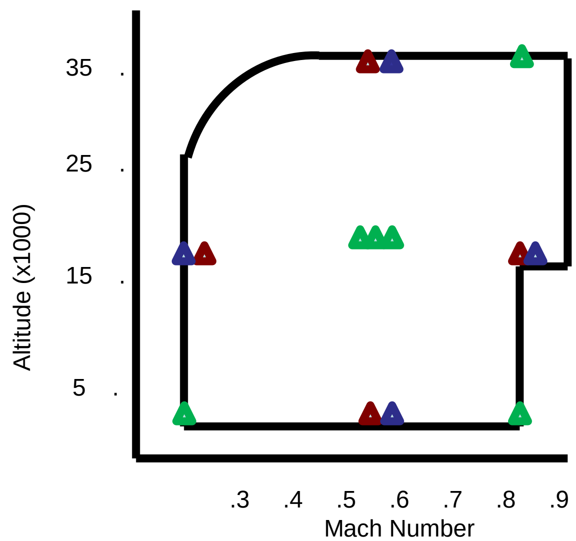
Multifactor Interaction Model

$$PSD = .081 + .000032\ Altitude + 1.081\ Airspeed + 1.203\ AoA + 1.2\ Airspeed * AoA + 1.32\ Airspeed^2$$



Response Surface Designs

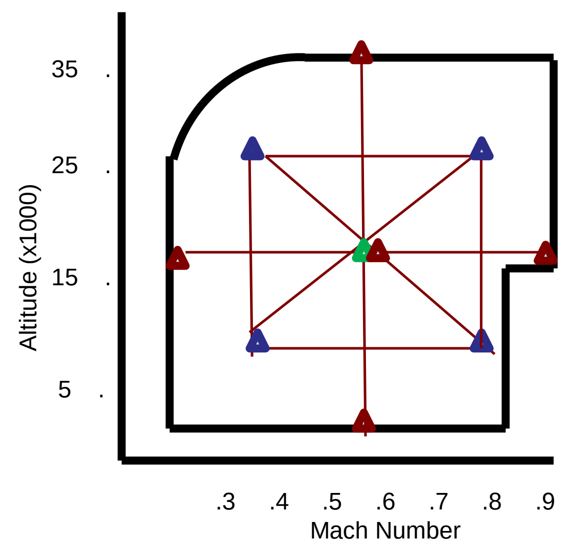
Box - Behnken



- AoA low
- AoA mid
- AoA high

Evaluates 3 factors w/ 15 points – does not evaluate edges of AoA envelope

Central Composite - Design



- **Experimental Design**
  1) **2 level factorial (▲)= $2^k = 8$**
  2) **Center point (▲)**

$$N=4\sqrt{nf+1} - 2k = 6$$

  3) **Axial points (▲)**

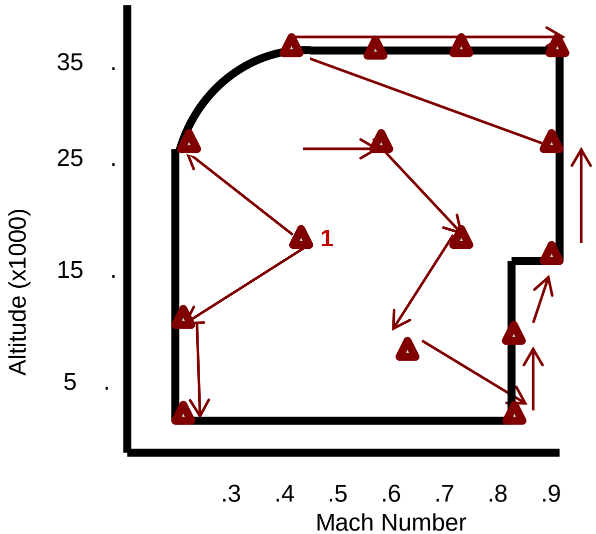
$2k = 6$

Total points = 20

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

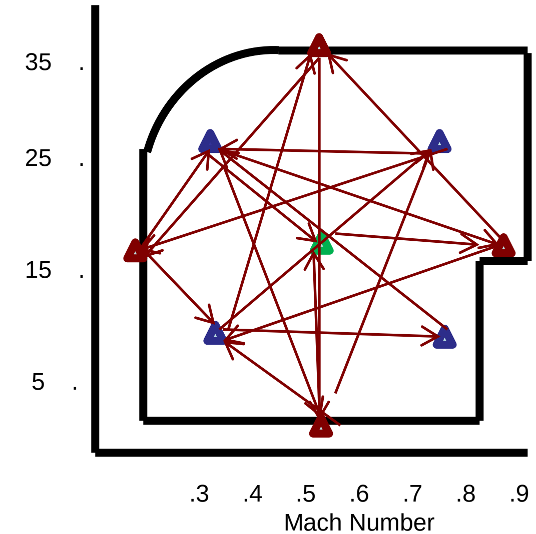
Execution Comparisons

One Factor At a Time - Execution



- **Progresses from Pt 1 "heart" to edges of envelope in efficient manner**
- **Limits safety risk – enables build-up to higher risk points**
- **Limitations:**
  - **May have unneeded points**
  - **Main effects only (No 2 factor interactions)**

Central Composite - Execution



- **Supports main effects, factor interactions**
- **Randomization washes out "nuisance factors"**
- **Limitations:**
  - **No safety build-up**
  - **Model output may not represent non linear "edge of the envelope"**
  - **Randomization drives inefficient execution**

Summary of DoE Approaches

Method	# of Points	%	Time (mins)	%	Cost ($)
OFAT	30	----	75	----	6250
Full Factorial	32	+ 6%	239	+ 68%	20000
Box Behnken	15	- 50%	90	+ 17%	7500
Central Composite Design	20	- 33%	112	+ 33%	9300

Execution
- **2500 ft / min altitude change**
- **1 min between AoA change**
- **2 min for min to max speed change**
- **Aircraft and range costs $5000/hr**

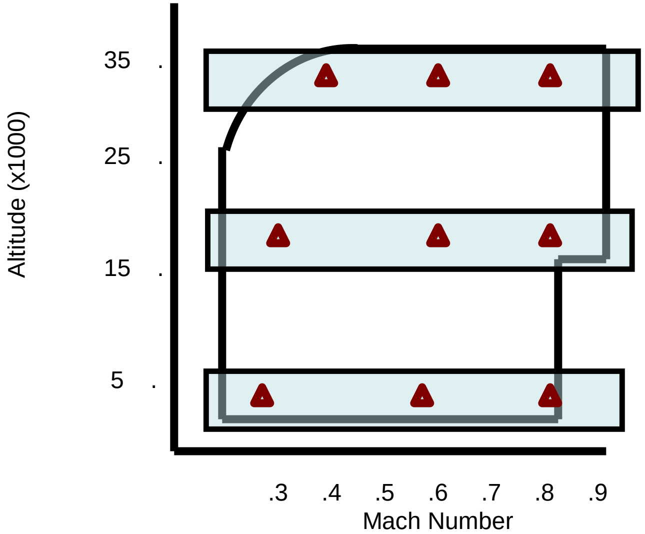
DoE Approaches – Split Plots

- Developed from agriculture experiments
- Randomization not practical
  - Hard to Change Variables set as “Whole Plots”
  - Easy to Change variables set as “Split Plots”

- May show value of DoE for DT&E with limited randomization
  - Not widely demonstrated in DT&E
  - Enables analysis of factor interactions at edges of envelope
  - Enables sequential safety build-up & execution efficiency
  - Uncontrolled variables confounded with Whole Plot variable

- Split – Split plot and Strip- Split plot designs – multiple “HTC” factors

http://agronomyday.cropsci.illinois.edu/2001/morrow-plots/



THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

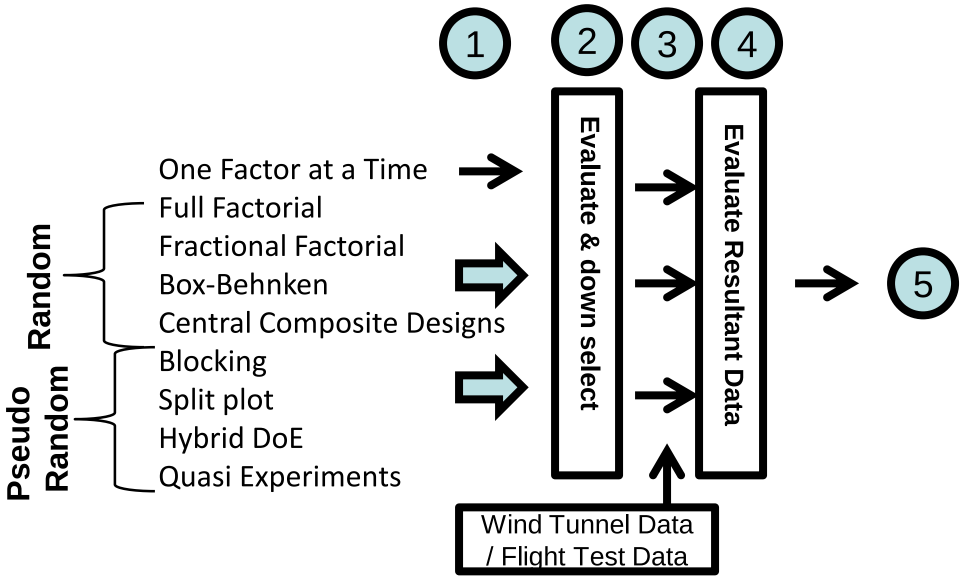
Future Study

Research Question

What experimental designs are efficient for testing prototypes when randomization of data is not desired?

Research Model / Approach

1) Utilize multiple methods to design experiment, including OFAT, Randomized DoE, and Pseudo-random methods.
2) Evaluate Methods for # of points. Down select to 3 methods
3) Demonstrate 3 methods with data set
4) Evaluate resultant data
5) Draw conclusions relative to research question and hypotheses.



THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Summary

- Long history of OFAT approach to Experimental & Developmental T&E
- T&E design should match system under test & environment
  - DoE often not optimal due to randomization & replication
- Advanced DoE techniques show promise
  - Increased cost & schedule efficiency ?
  - Limit randomization & replication
  - Enable evaluation of multifactor interactions
- Future work
  - Focus on aircraft performance & flying qualities applications
  - Demonstrate Blocking & Split Plot techniques
  - Potential for wind tunnel or open air applications

•Contact: pfiorenza@gwmail.gwu.edu
paul.fiorenza@us.af.mil

Contact Information

Paul Fiorenza, Col, USAF, is an Experimental Test Pilot at the Air Force Flight Test Center. He has over 2700 flight hours in more than 30 aircraft types and has led operational and developmental flight test programs on both fixed wing and rotary wing platforms across flying qualities, performance and systems integration disciplines. He received a B.S. (1992) in Computer Engineering from Clarkson University, Potsdam, NY, is a graduate of US Naval Test Pilot School (2003), Patuxent River, MD, received an M.S. (2008) in Aviation Systems from University of Tennessee Space Institute, Tullahoma, TN, and an M.S.(2012) in Strategic Studies from Air University, Air War College, Maxwell, AFB, Al. He is currently a Ph.D. candidate in Systems Engineering at The George Washington University with a dissertation focused on experimental design approaches for physical prototype systems.

pfiorenza@gwmail.gwu.edu

REFRENCES

- DoDI 5000.02 Jan 7, 2015

- English, T. Simpson, R. Landman, D. Parker, P (2012) An Efficient Split-Plot Approach for Modeling Nonlinear Aerodynamic Effects Quality Engineering 24:522-530

- Hill, R. R., Leggio, D. A., Capehart, S. R. and Roesener, A. G. (2011), Examining improved experimental designs for wind tunnel testing using Monte Carlo sampling methods. Qual. Reliab. Engng. Int., 27: 795–803. doi: 10.1002/qre.1165

- Johnson, R.T., Hutto, G.T, Simpson, D.C., Montgomery, D.C. (2012), Designed Experiments for the Defense Community. Quality Engineering, 24:60-69

- Joao D, Afzal S, Benjamin B. Aircraft Wind Tunnel Characterization Using Modern Design of Experiments. (2013) 54th AIAA/ASME/ASCE/AJS/ASC Structures, Structural Dynamics, and Materials Conference, Boston, MA

- Kraft, E.M. (2010) After 40 Years Why Hasn't the Computer Replaced the Wind Tunnel? ITEA Journal, 31: 329-346

- Kass, Richard (2008) A Framework For Understanding Experiments, ITEA Journal 29: 167-174

- Kass, Richard (2008) Tests and Experiments: Similarities and Differences ITEA Journal 29 294-300

- Parker, P. Kowalski, S. Vining, G (2007) Construction of Balanced Equivalent Estimation Second-Order Split Plot Designs Technometrics 49: p.56

- Simpson JR, Listak CM, Hutto GT. Guidelines for planning and evidence for assessing a well-designed experiment. *Quality control and applied statistics*. 2014;59(5):511-512

- Tucker, A. A. and Dagli, C. H. (2009), Design of Experiments as a Means of Lean Value Delivery to the Flight Test Enterprise . Systems Engineering, 12: 201–217.

- Tucker, A.A., Hutto, G.T, Dagli, C.H. (2010) Application of Design of Experiments to Flight Test: A Case Study, Journal of Aircraft, 47:458-463

- Woolf R. Applications of Statistically Defensible Test and Evaluation Methods to Aircraft Performance Flight Testing. (2012) AIAA 28th Aerodynamic Measurement Technology, Ground Testing, and Flight Testing Conference