# Aerospace and Telecommunications Engineering Support Squadron

# Canadian Forces Generic Bolt Hole Eddy Current Probability of Detection Study

## ASIP 2007

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# Outline

- Introduction
- Empirical Bolt Hole Eddy Current (BHEC) MIL HDBK 1823 Reliability Assessment
  - Design of Experiments (DoE)
  - Results
- Probability of Detection (PoD) Modeling
  - Why model?
  - Design of Experiments
  - Results
- So where is this going?
- Remaining Work
- Conclusion

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# Introduction

- What is PoD (in layman's terms)?
- Why do we need PoD?
- Why Model PoD?
  - MAPoDWG

www.cnde.iastate.edu/research/MAPOD

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# Introduction

- This project was funded by the Canadian Air Force Director General of Aerospace Equipment Program Management (DGAEPM) to:
  - Reassess (and hopefully reduce) the current $a_{90/95}$ assumption of 0.050" for Bolt Hole Eddy Current (BHEC) Inspections
  - Investigate Probability of Detection (PoD) modeling to be able to apply PoD results to other similar structure
    - i.e. Lockheed Martin box wing structures of the C130 and CP140 (P3)

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# Empirical Study - DoE

- Test pieces were manufactured to represent the wing box structures of the C130 and the CP140 (P3)
- Test coupons included both EDM notches and lab grown cracks
- Test Coupons
  - Al 7075-T6
  - 3/16” fastener holes
  - 0.090” and 0.312” thickness (representing range of typical wing plank/spar/web thicknesses in CP140 and C130)
  - Two layer stack up

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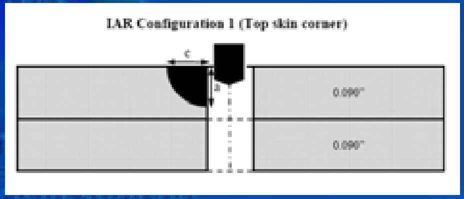
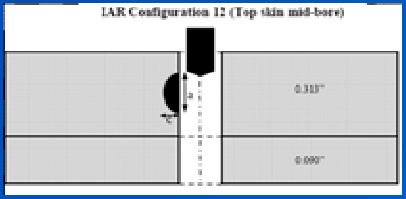
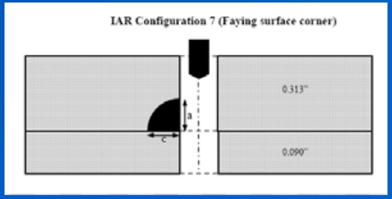
# Empirical Study - DoE

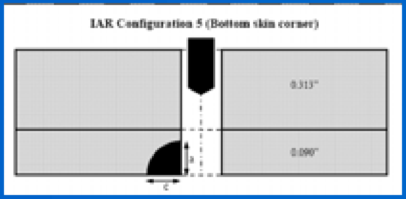
# Empirical Study - DoE

- Four different coupon configurations
  - $1^{st}$ Layer top surface corner cracks
  - $1^{st}$ Layer mid-bore cracks
  - $1^{st}$ Layer faying surface corner cracks
  - $2^{nd}$ Layer back surface corner cracks
- EDM notches are also included each of the above configurations
  - Allows for direct comparison of EDM indications to crack indications
  - The EDM notches were mixed in with the cracks during the actual inspections

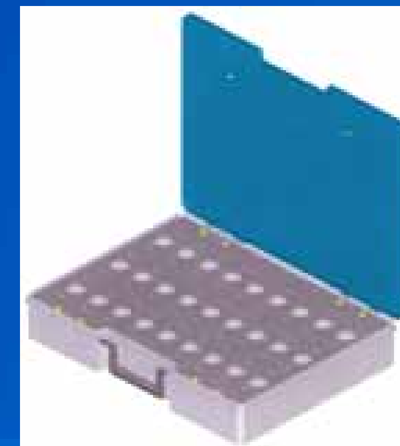


# Empirical Study - DoE

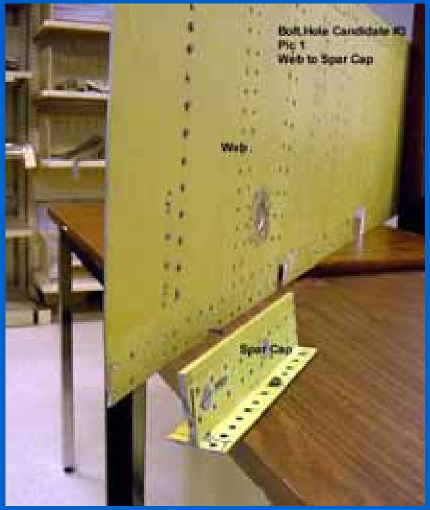


**Inspector Test Result Data Sheet**

| | | | | | |
|---|---|---|---|---|---|
| Date | | | Equipment | | |
| Inspector ID: | | | Probe | | |
| Organization | | | Frequency: | Threshold | |
| Box ID | | | Magnitude Scale | Noise Level | |
| | Test Identification | | | Comments | |
| Box and Set Number | Crack indication (Y/N) | Signal Magnitude | Phase Angle | | |
| A01 | | | | | |
| A02 | | | | | |
| A03 | | | | | |
| A04 | | | | | |
| A05 | | | | | |
| A06 | | | | | |
| A23 | | | | | |
| | | | | | |
| A24 | | | | | |
| A25 | | | | | |
| A26 | | | | | |

# Empirical Study - DoE

- Real P3 structure was chosen that had relatively few defects (as determined by BHEC, LPI, and enhanced visual inspection)
- EDM defects inserted and replicas made
- Structure reassembled with minimum amount of fasteners
- Inspected as per the Canadian Air Force Bolt Hole Inspections (draft GEN 74E)
- Performed fractography on all the fastener holes upon completion of the inspections to ascertain bolt hole condition
- Allows for direct measurement of noise in aged service structure
  - EDM notches in new material vs. EDM notches in aged/in-service material



# Empirical Study - DoE

- So what do we have?
  - Each of the four configurations consists of 450-500 coupons
    - 60-80 lab grown cracks
    - 40-55 EDM notches
    - Distribution of crack sizes between 0.005” and 0.150”
    - Each of these sets were inspected by 7-24 inspectors
  - The retired P3 structure consisted of 151 holes
    - 40 EDM notches
  - In the end over 30000 data points were collected

# Empirical Study - Results

- Three different software codes were used to analyze the data
  - National Research Council of Canada (NRCC) code for hit-miss data
  - NRCC code for â vs. a data
  - Draft MIL HDBK 1823 software
- There are many ways to estimate the PoD
  - depends on the type of data, the functional form, the thresholds and confidence bounds calculation
- Only the data analyzed with the draft MIL HDBK 1823 software will be presented
  - â vs. a data, log-logistic functional form, and maximum likelihood ratio determination of confidence bounds

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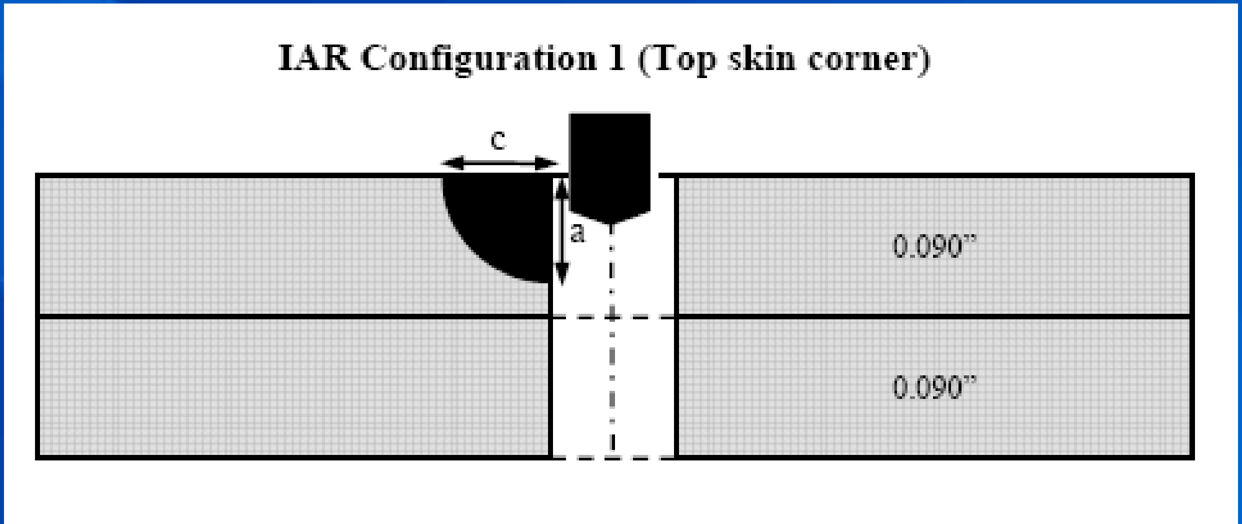
# Results for Crack Depth c




| Lab Grown Cracks | EDM Notches |
|---|---|
| $a_{90}$ = 10.7 mils | $a_{90}$ = 17.6 mils |
| $a_{90/95}$ = 16.8 mils | $a_{90/95}$ = 26.7 mils |
| False call = 0.49% | False call = 0.49% |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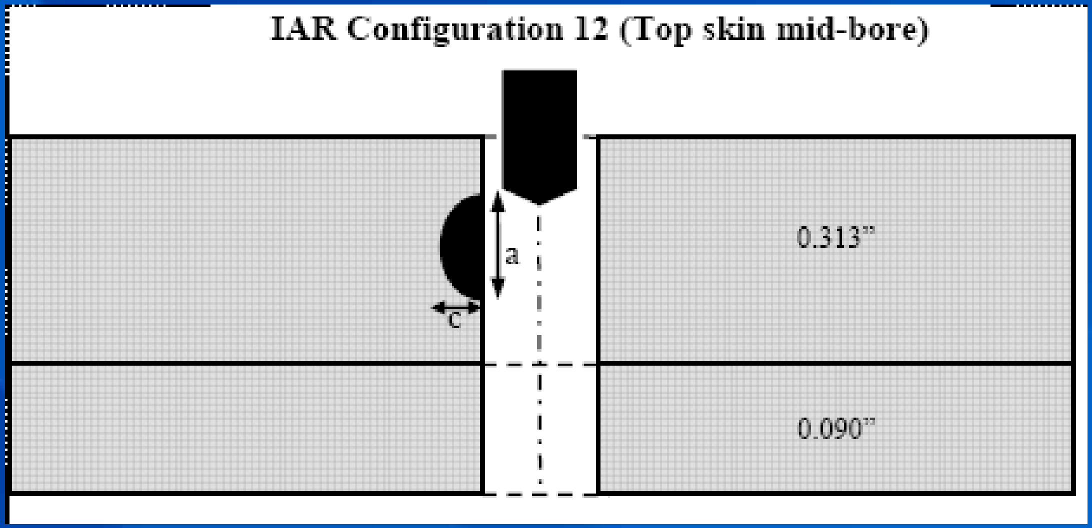
# Results for Crack Depth c




**Lab Grown Cracks**

$a_{90}$ = 13.2 mils

$a_{90/95}$ = 25.3 mils

False call = 0.08%

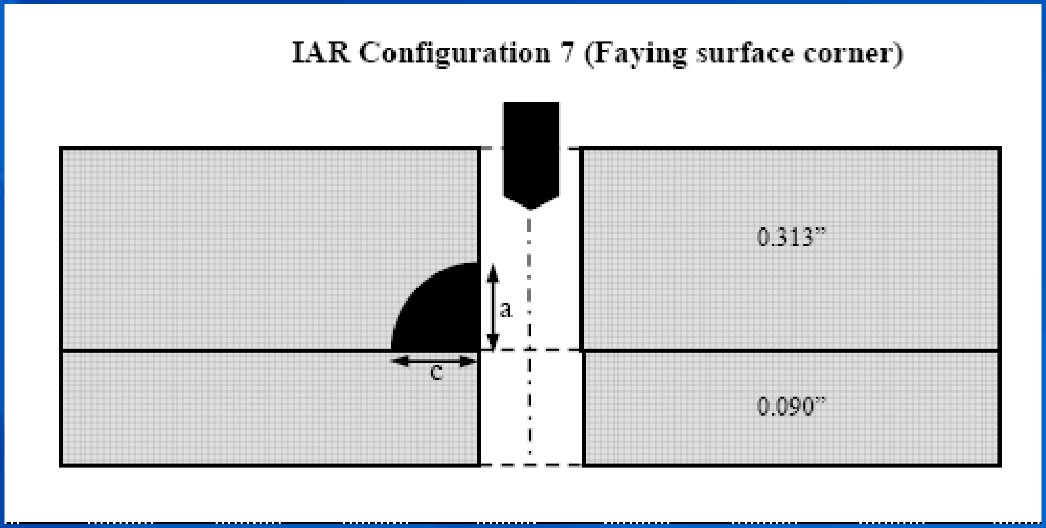
**EDM Notches**

$a_{90}$ = 18 mils

$a_{90/95}$ = 30.0 mils

False call = 0.08%

# Results for Crack Depth c




Lab Grown Cracks

$a_{90}$ = 9.3 mils

$a_{90/95}$ = 16.4 mils

False call = 0.77%

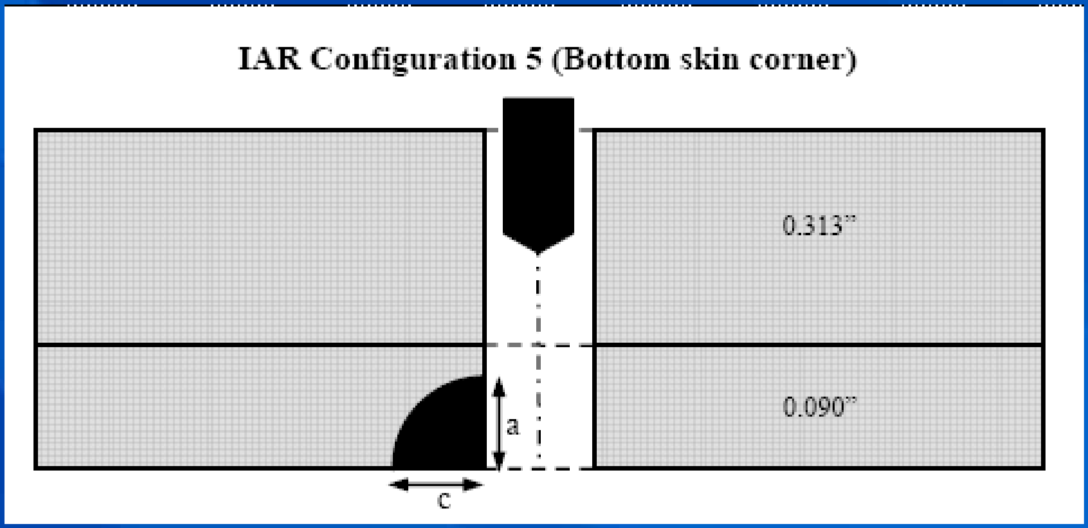
EDM Notches

$a_{90}$ = 22.3 mils

$a_{90/95}$ = 33.1 mils

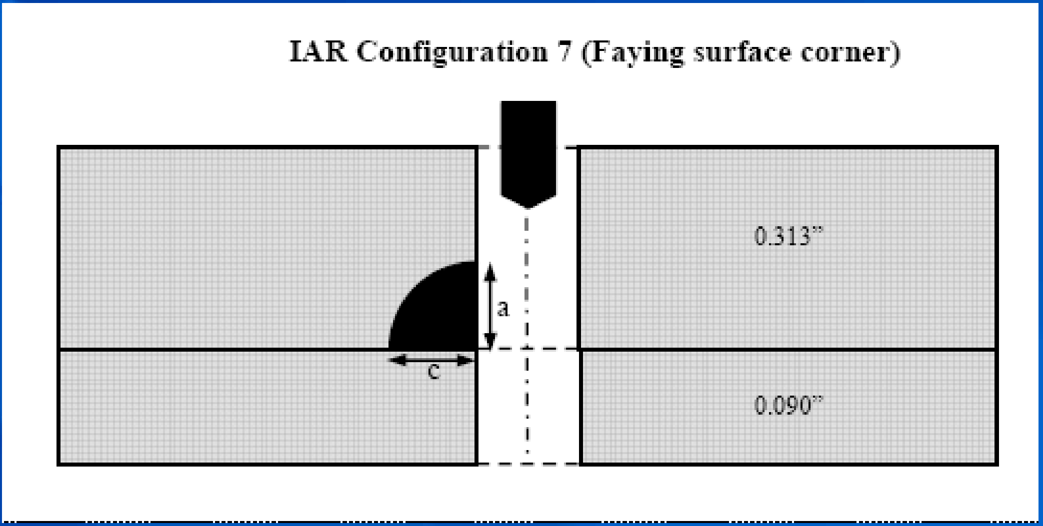
False call = 0.77%

# Results for Crack Depth c




| Lab Grown Cracks | EDM Notches |
|---|---|
| $a_{90}$ = 6.7 mils | $a_{90}$ = 16.8 mils |
| $a_{90/95}$ = 11.1 mils | $a_{90/95}$ = 25.0 mils |
| False call = 0.05% | False call = 0.05% |

# Results – EDM notches in Retired P3 wing structure




Lab Grown Cracks

N/A

EDM Notches

$a_{90}$ = 26 mils

$a_{90/95}$ = 32 mils

False call = 6.46%

# Empirical Study - Results

- Location of defect within the hole is a factor
- Cracks less < 0.040" gave a larger â than corresponding EDM notches

Lab Grown Cracks and EDM Notches in New Material

| Layer | Surface | EDM $a_{90/95}$ | Crack $a_{90/95}$ | False Call Rate |
|---|---|---|---|---|
| 1st | Upper | 27 | 17 | 0.49% |
| 1st | MidBore | 30 | 25 | 0.08% |
| 1st | Faying | 33 | 16 | 0.77% |
| 2nd | Back | 25 | 11 | 0.05% |

EDM Notches in Retired P3 Wing Structure

| Layer | Surface | EDM $a_{90/95}$ | Crack $a_{90/95}$ | False Call Rate |
|---|---|---|---|---|
| 1st | Faying | 32 | N/A | 6.46% |

# Empirical Study - Results

- Many factors must be taken into consideration when using this data
  1. Only the data from the first layer upper surface cracks and the second layer lower surface cracks are directly comparable (same set of specimens in different locations)
  2. The EDMs and cracks had different crack size distributions for the same configuration
     - Mean curves are dependent on the crack size distributions
     - Therefore the curves cannot be directly compared
  3. There were less data points for the EDMs as compared to the cracks
     - Effects confidence bounds

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# Empirical Study - Results

4. The distribution of crack sizes is different between the configurations
    - The mid-bore cracks had a large number of large cracks (0.100' – 0.150' range) and less smaller cracks (0.010" – 0.020") -> this greatly influenced the PoD calculations
    - The faying surface corner cracks had a much larger number of smaller cracks as compared to the two other corner cracks configurations

**$a_{90/95}$ by itself does not provide sufficient information to be properly applied in risk analysis**

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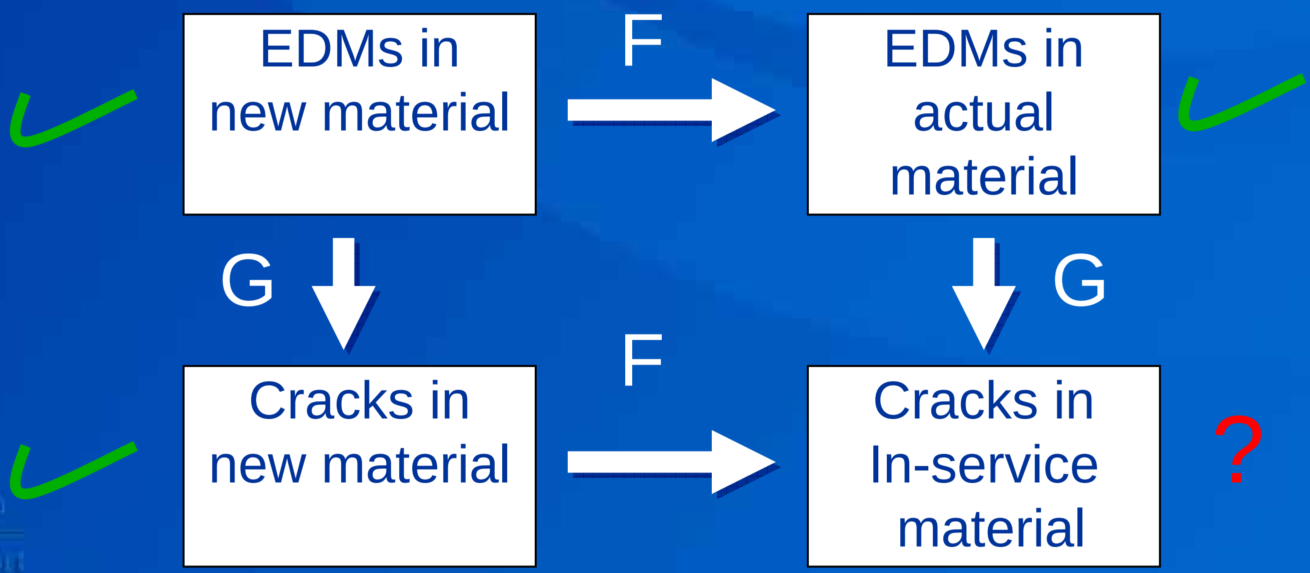
# Empirical Study - Results

- At this point, 3 different inspection sets have been evaluated:
  - Lab grown cracks in new material
  - EDM notches in new material
  - EDM notches in in-service material
- From the data a reliability assessment of cracks in real structure can be estimated



# Why model PoD?

- Represents an inexpensive and more timely alternative to costly experimental PoD studies
- Has the potential to partially substitute and complement experimental PoD data
- Reduces cost, effort, resources
- Allows portability of PoD information across similar structures
- Helps in damage tolerance calculations and increases platform availability

Conditions:

- Validate model on a reduced set of specimens
- Use the same variables as the experimental study
- Simulate the same signal features of interest

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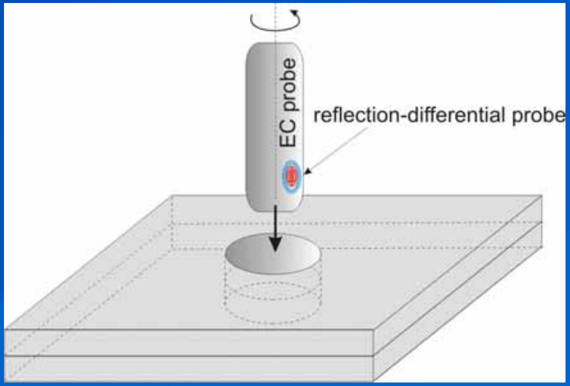
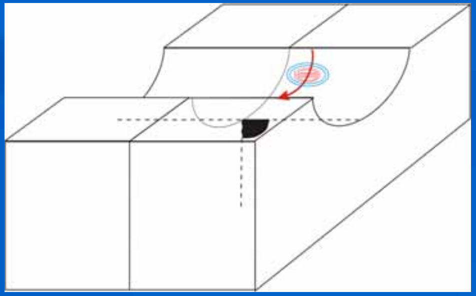
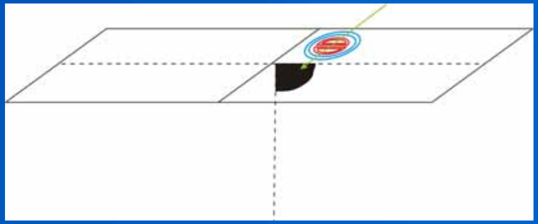
# PoD Modeling - DoE

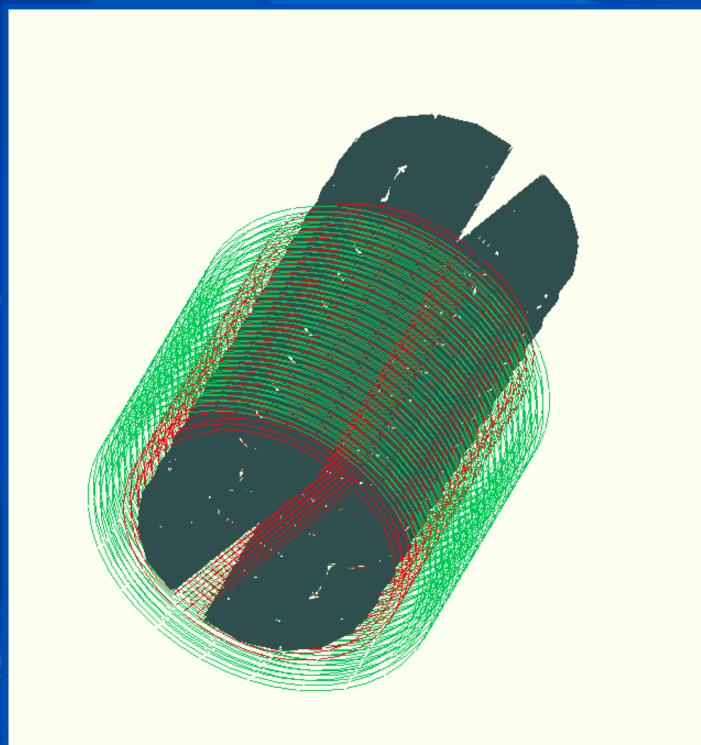
- Used ECSim package (ISU) to model:
    - Defect length
    - Defect depth
    - Probe lift-off
    - Off-centre scanning
    - Frequency
    - Probe tilt
    - Material conductivity

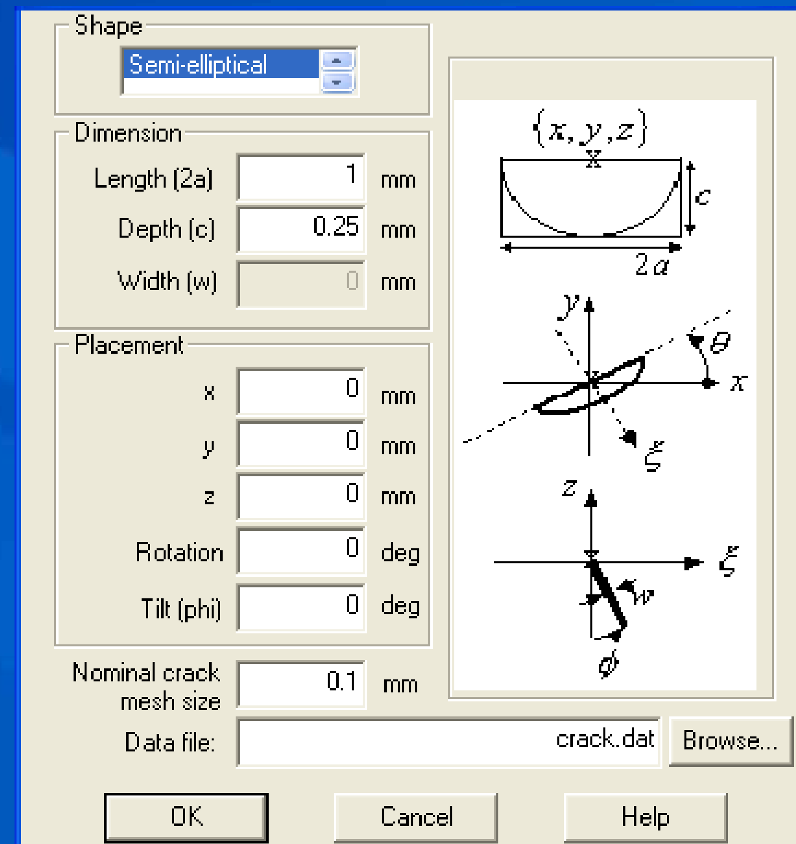


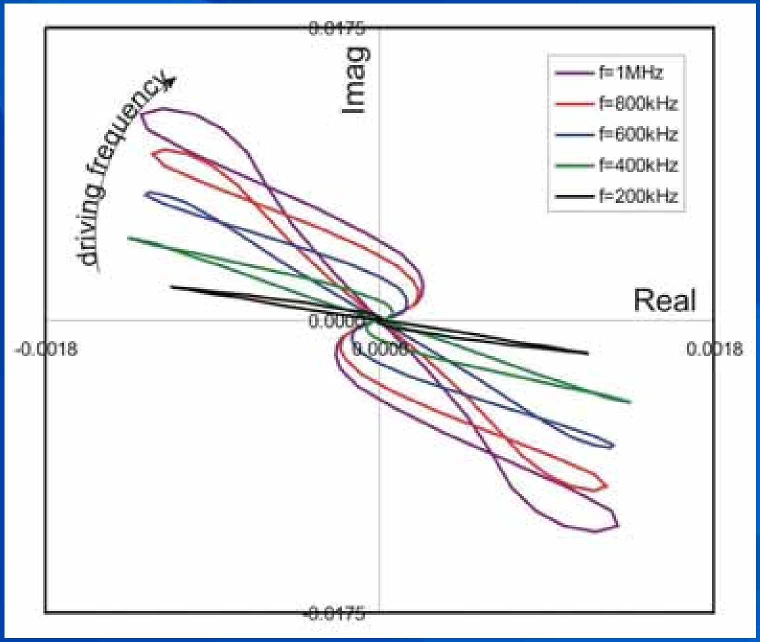


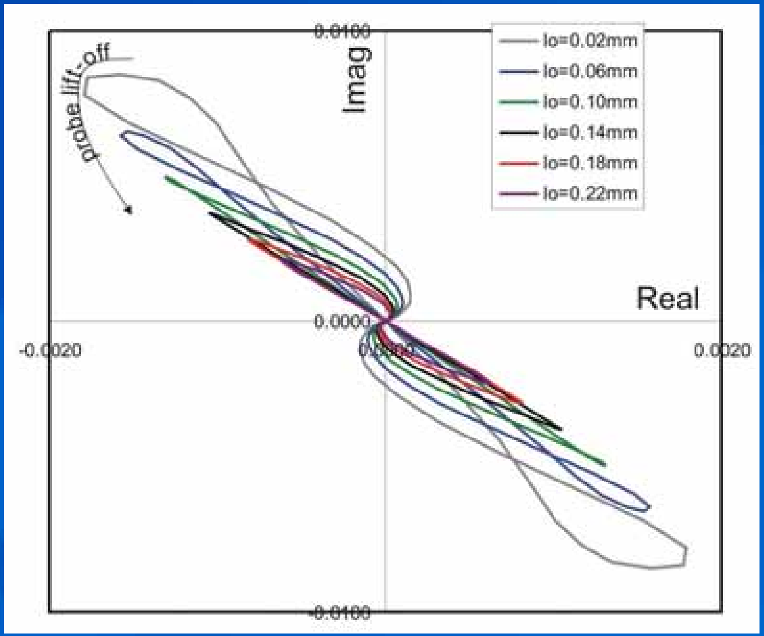
# PoD Modeling - DoE

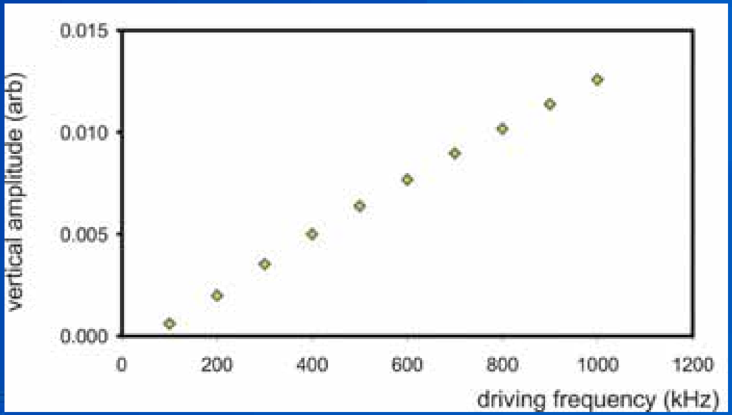


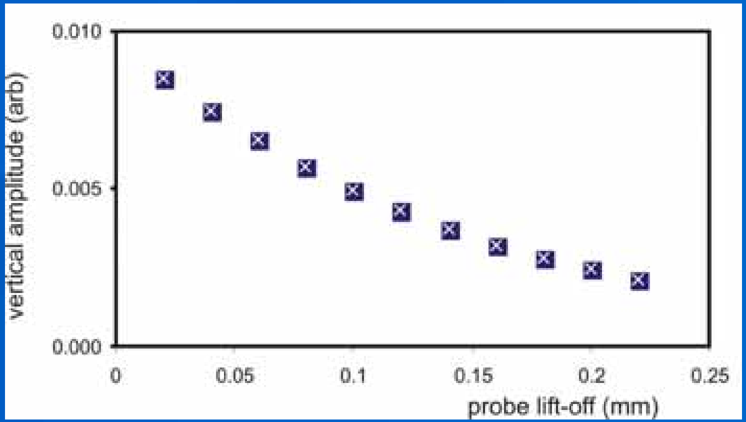


# PoD Modeling – Results



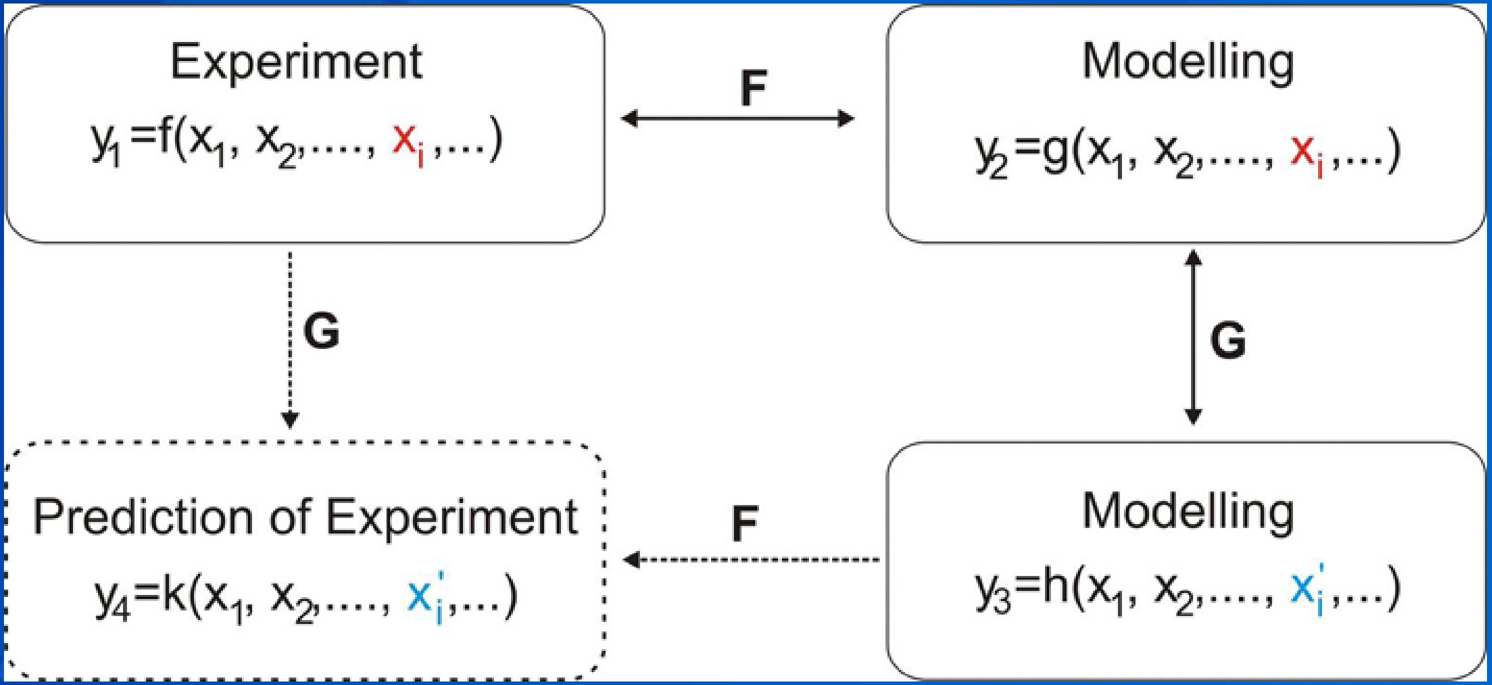



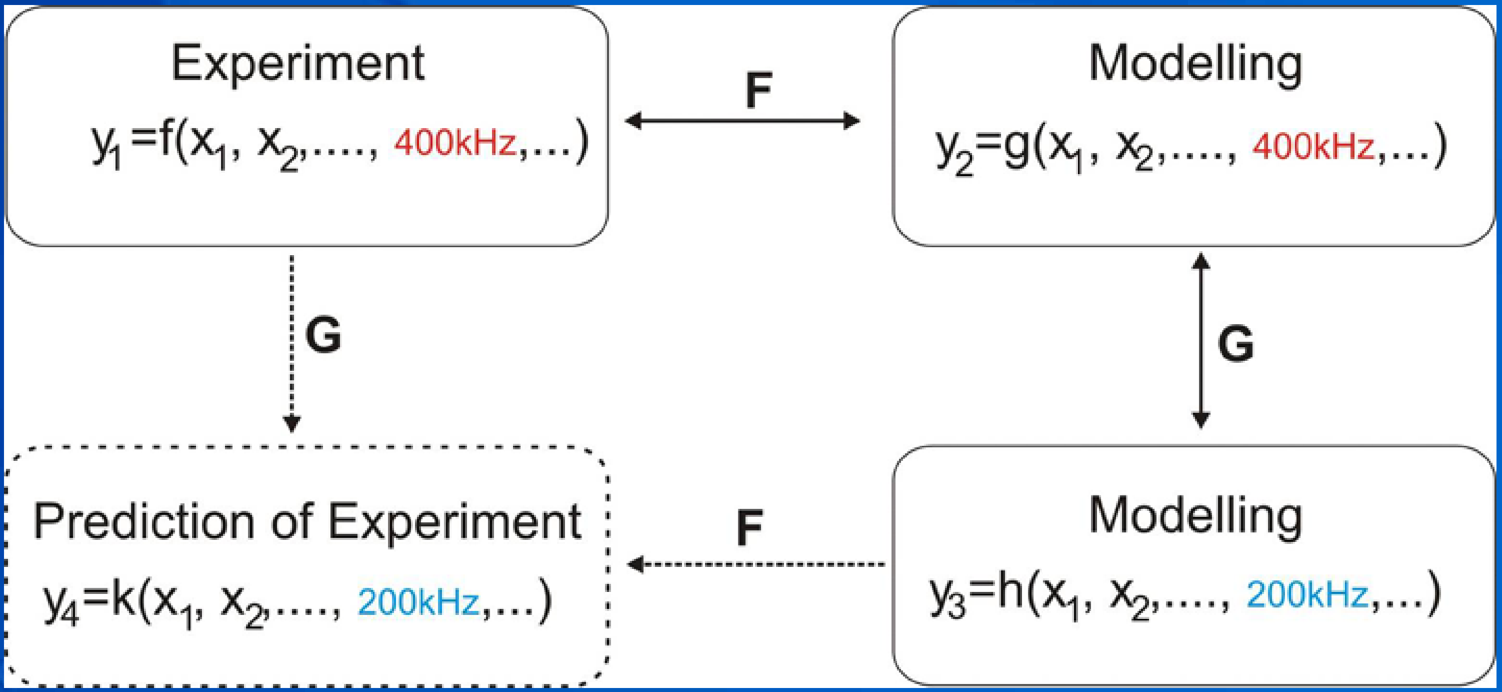
# PoD Modeling

General principles of using numerical-based approach for estimating PoD



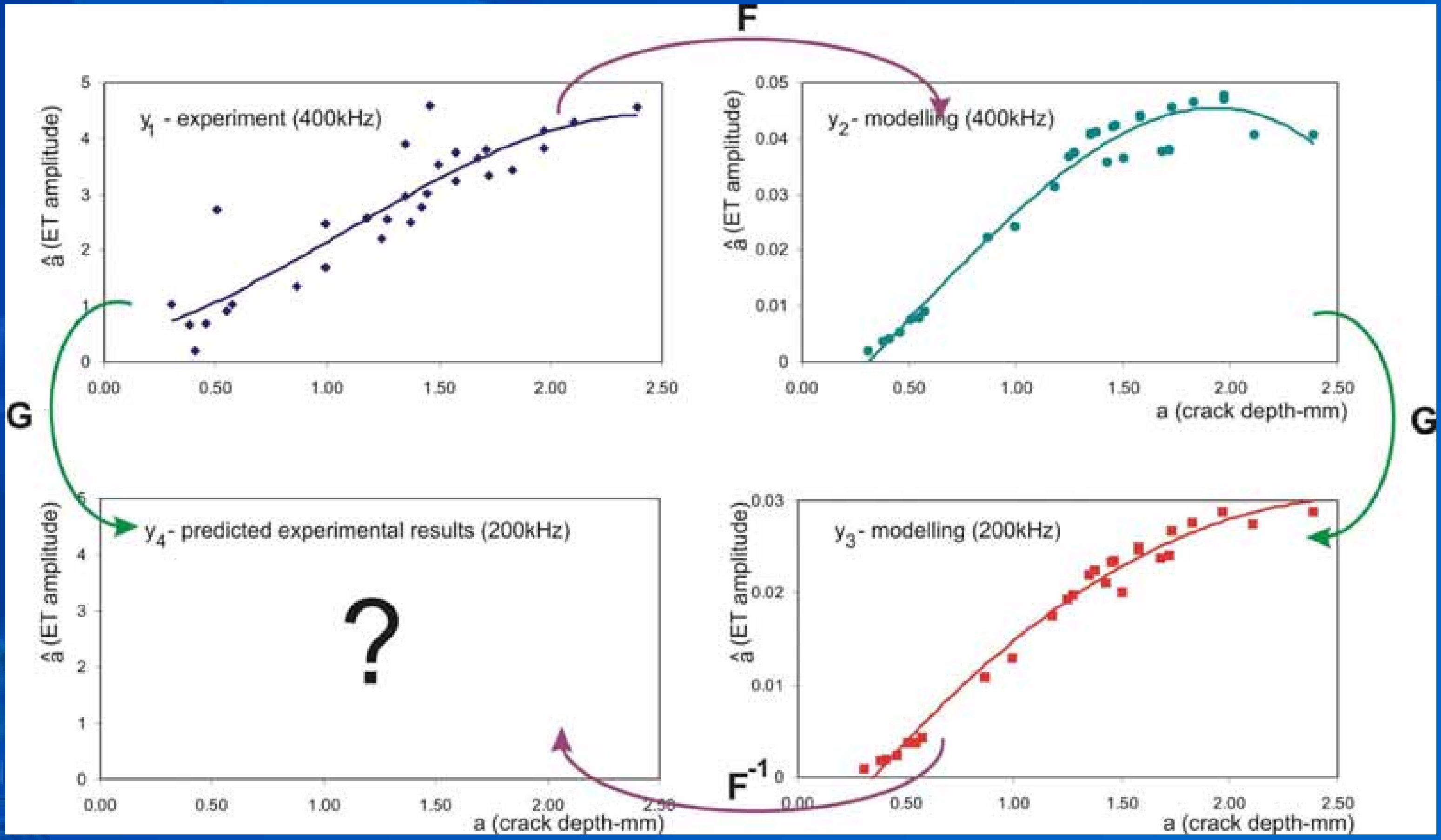
# PoD Modeling

Consider only a change in the driving frequency:



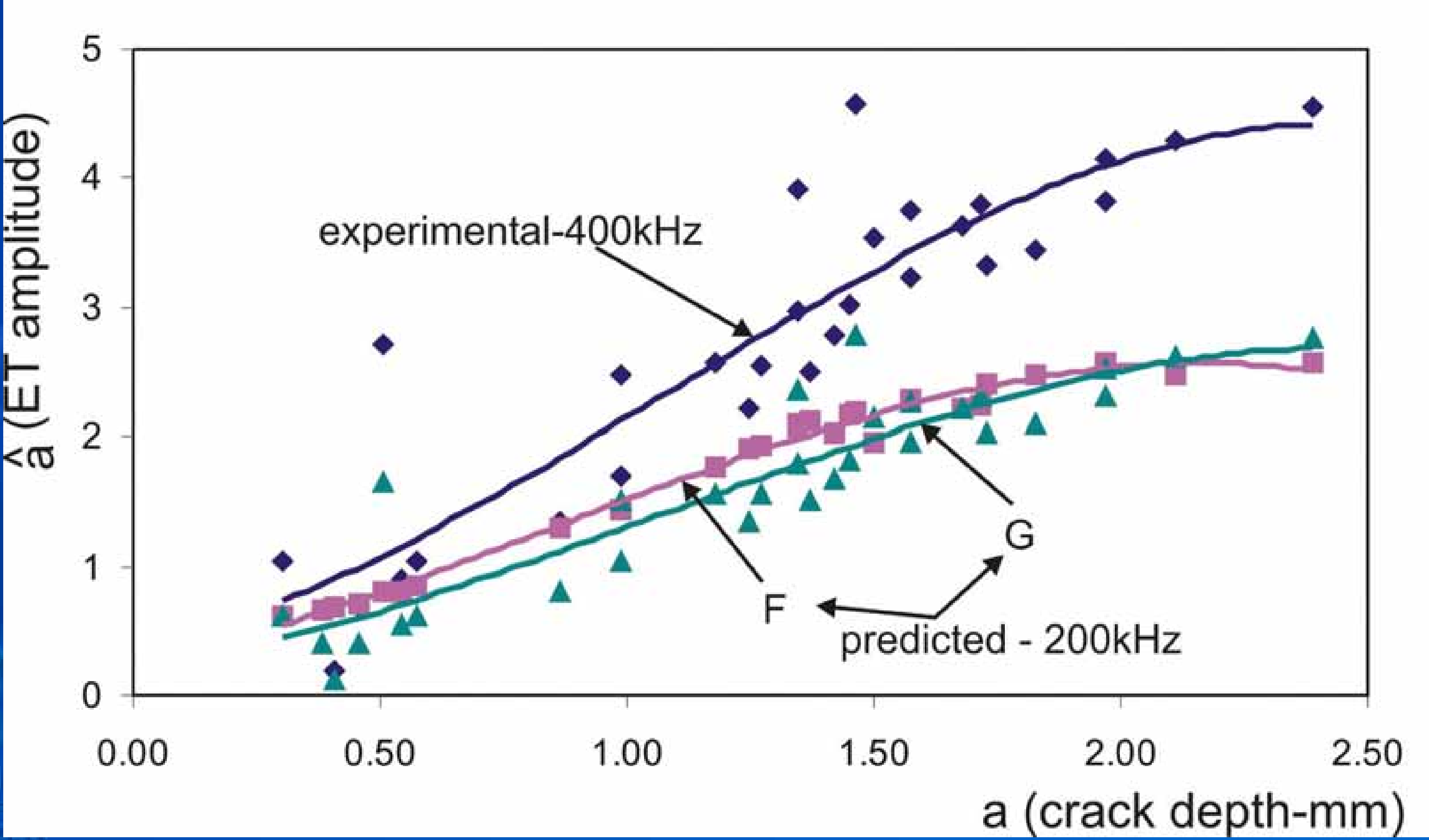
# PoD Modeling

- Example

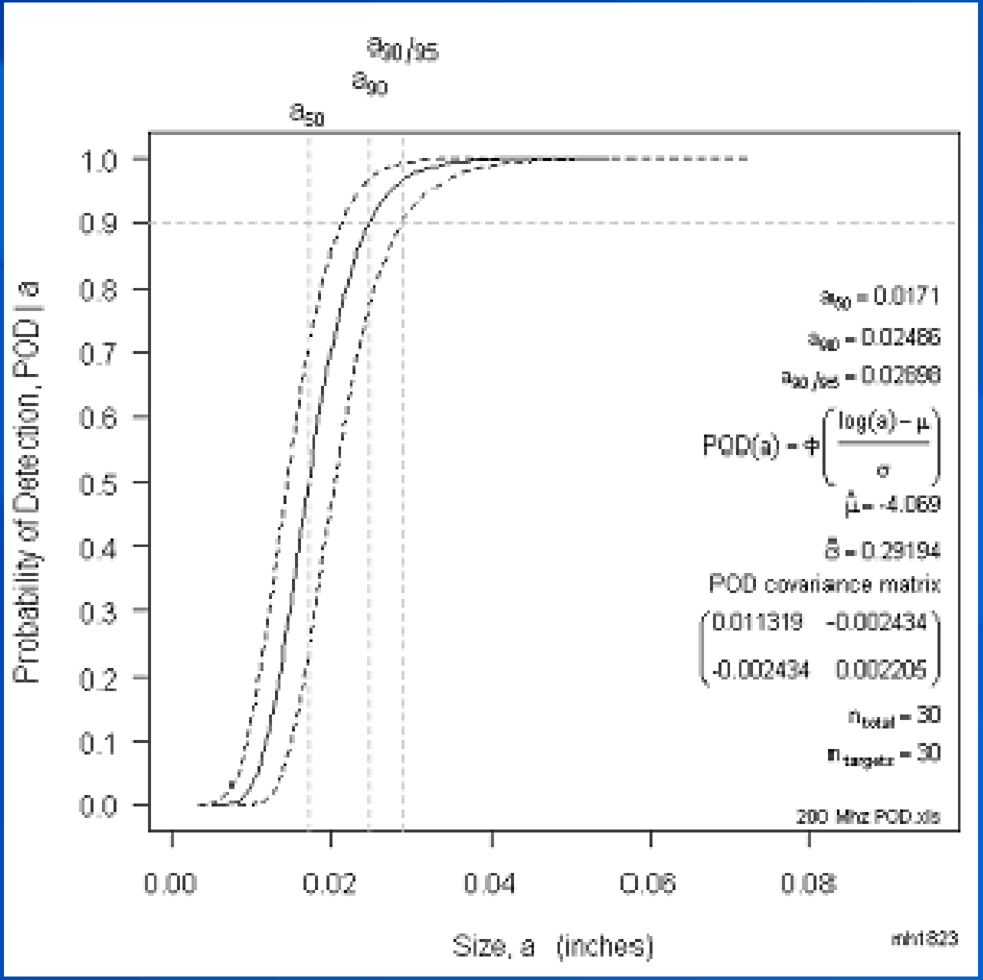


# PoD Modeling

- Example



# PoD Modeling




PoD curve for 200kHz (as generated from the model predicted â data)

# So where is this going?

- The reliability assessment in defect detection in real structures can be estimated in five manners:

1. Developing a transfer function from the EDMs in new material to EDM in actual material and applying this function to the cracks in the new material (accounts for hole quality)
2. Developing a transfer function from the EDMs in the new material to the cracks in the new material and applying this function to the cracks in the new material (accounts for crack/EDM relationship)
3. Make noise measurements in the actual material and add these measurements to the â vs. a data for the lab grown cracks
    1. This can be accomplished using the new MIL-HDBK-1823 software (mh1823)
    2. This is more or less a variation of option 1
4. Using a validated model to predict the data
5. A combination of any of the above

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# Remaining Work

- Estimate the PoD for cracks in real structure using the already generated empirical data (Transfer Function Approach)
  - Compare this to the noise analysis tool of the draft MIL HDBK 1823
- Validation of current model (using EC Sim) by experiment (Model Assisted Approach)
  - i.e. conduct a limited scope PoD for the mid-bore cracks at 200kHz and compare to the modeled PoD

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# Conclusion

- There are many different ways to determine $a_{90/95}$
  - Understanding how the number is generated is critical to proper application in risk analysis of in-service aerospace structures
  - Empirical studies are only valid for applications of the same parameters
- Estimates of $a_{90/95}$ can be determined in three different manners:
  - Transfer Functions from existing PoD data
  - Model Assisted approach
  - A combination of both
- Once the processes are validated, estimates of $a_{90/95}$ have the potential to significantly reduce the cost and time associated with empirical PoD studies
- The development of Transfer Functions and Model Assisted PoD methodologies is still ongoing

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# Questions?