Transfer Function Models for Using Empirical and Physics-Based Simulation Signal Response Data

Ajay M. Koshti, D. Sc. PE
NASA Johnson Space Center, Houston

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Summary

- In many situations, real or induced flaws such as tight cracks with known morphology cannot be manufactured in part geometry specimens or in real parts.
  - Typically, surface fatigue cracks are manufactured in simple geometry specimens such as flat plates, dog-bone shaped flat or cylindrical specimens. If a nondestructive evaluation (NDE) technique is required to provide a reliably detectable flaw size, denoted as $a_{90/95}$, for induced flaws in a part, then a direct method for qualifying the NDE procedure is to use appropriate induced flaw specimens and perform NDE procedure demonstration on the specimens.
- Probability of detection (POD) analysis of the empirical data may provide estimation of $a_{90/95}$.
  - This approach is described as direct POD demonstration testing, which may follow guidelines of MIL-HDBK-1823.
- This paper considers a case, where embedded tight cracklike induced flaws are to be detected reliably using a signal response based NDE procedure.
  - Here, it is assumed that it is not practical to make surface or embedded induced flaw specimens in part geometry or configuration.
  - Therefore, a direct POD demonstration testing cannot be undertaken.
  - It is also assumed that simulation of signal response is possible for both surface and embedded induced flaws in part geometry specimens using a physics-based model.
- The proposed approach for NDE procedure qualification uses artificial flaws in simple geometry and part geometry specimens, and induced flaws in the same type of simple geometry specimens.
  - Signal response data is taken on all sets of artificial and induced flaws in simple geometry and part geometry specimens.
- Moreover, simulated signal response data is generated for surface and embedded flaws.
- Thus, a case of five signal response versus flaw size datasets is considered. Three of the datasets are empirical and two datasets are physics model-based simulation datasets.
- A method of devising and using transfer function calculation dataset blocks or steps to estimate the either the reliably detectable flaw size or the demonstration flaw size is provided.
- It is proposed for using in eddy current detection of far side flaws.

Objective

- Present a signal response transfer relationships models
- Present muti-step transfer function models
- Use simulated data to explain the models
  - Generate fictitious population data that follows transfer function assumptions
    - Assess selected sampling cases in determining flaw size estimate for
      - Forward case
        - Input flaw size: Target flaw size in part
        - Output flaw size: Mean predicted induced flaw size for demonstration in simple geometry specimen
      - Inverse case
        - Input flaw size: Mean induced flaw size for demonstration in simple geometry specimen
        - Output flaw size: Predicated 90/95 Target flaw size in part

Signal Response Variables

Table 1: Subscript convention for variables “x” and “y”

Flaw Type (Ternary)	Part Geometry (Binary)	Flaw Location (Binary)
e – artificial, machined, or Machined flaw	1 – simple geometry	1 – location 1 e.g., surface
c – induced or cracklike flaw	2 – part geometry	2 – location 2e.g., embedded
s – computer simulated flaw		

Table 2: Signal response variables for datasets and transfer variable blocks. Dataset blocks, Example 1

Block	Specimen Geometry	Location	Flaw Type	
1			Machined Flaw	Induced Flaw
	Simple Geometry, 1	Surface, 1	Dataset 1: $y_{e,1,1}$or	Dataset 3: $y_{c,1,1}$
	Part Geometry, 2	Surface, 1	Dataset 2: $y_{e,2,1}$	Dataset 4: $y_{c,2,1}$(output 1)
2			Computer Simulated Flaw	Machined Flaw
	Part Geometry, 2	Surface, 1	Dataset 5: $y_{s,2,1}$	Dataset 2: $y_{e,2,1}$
	Part Geometry, 2	Embedded, 2	Dataset 6: $y_{s,2,2}$	Dataset 7: $y_{e,2,2}$ (intermediate output 2)
3			Machined Flaw	Induced Flaw
	Simple Geometry, 1	Surface, 1	Dataset 1: $y_{e,1,1}$	Dataset 3: $y_{c,1,1}$
	Part Geometry, 2	Embedded 2	Dataset 7: $y_{e,2,2}$	Dataset 8: $y_{c,2,2}$(output 3)

Table 3: Generic transfer function block variable notation. Dataset blocks, Example 2.

Block	Binary Feature A (Geometry)	Binary Feature B (Location)	Ternary Feature C (Flaw Type)	
1			1 (EDM notch)	2 (Induced crack)
	1 (Tube, no weld)	1 (ID surface)	Dataset 1: $y_{v1,b1}$ or	Dataset 3: $y_{v3,b1}$
	2 (Tube, weld crown)	1 (ID surface)	Dataset 2: $y_{v2,b1}$	Dataset 4: $y_{v4,b1}$ (Output 1)
2			3 (Simulated flaw)	1 (EDM notch)
	2 (Tube, weld crown)	1 (ID surface)	Dataset 5: $y_{v1,b2}$	Dataset 2: $y_{v3,b2}$
	2 (Tube, weld crown)	2 (Embedded close to ID)	Dataset 6: $y_{v2,b2}$	Dataset 7: $y_{v4,b2}$ (output 2)
3			1 (EDM Notch)	2 (Induced Crack)
	1 (Tube, no weld)	1 (ID surface)	Dataset 1: $y_{v1,b3}$	Dataset 3: $y_{v3,b3}$
	2 (Tube, weld crown)	2 (Embedded close to ID)	Dataset 7: $y_{v2,b3}$	Dataset 8: $y_{v4,b3}$ (Output 3)

Examples of Dataset Blocks

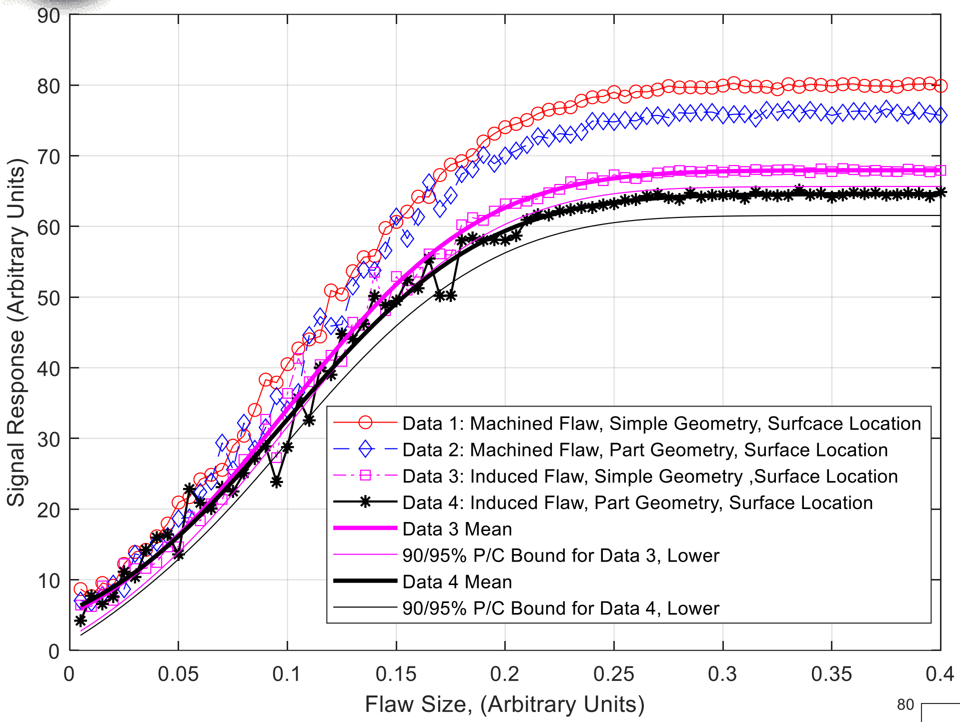
Table 4: Dataset blocks, Example 3

Block	Specimen Geometry	Location	Flaw Type	
1			Machined Flaw	Induced Flaw
	Simple Geometry, Plate, 1	Plate Farside Surface, 1	Dataset 1: $y_{e,1,1}$or	Dataset 3: $y_{c,1,1}$
	Part, Tube, 2	Tube I.D. Surface, 1	Dataset 2: $y_{e,2,1}$	Dataset 4: $y_{c,2,1}$(output 1)
2			Computer Simulated Flaw	Induced Flaw
	Part, Tube, 2	Tube I.D. Surface, 1	Dataset 5: $y_{s,2,1}$	Dataset 4: $y_{c,2,1}$
	Part, Tube, 2	Tube Embedded, 2	Dataset 6: $y_{s,2,2}$	Dataset 8: $y_{c,2,2}$(output 2)

Table 4: Signal response variables for datasets and transfer variable blocks. Dataset blocks, Example 4.

Block	Location	Set-up	Flaw Type	
1			EDM Notch (en)	Fatigue Crack (fc)
	Plate Farside (g1)	Set-up 1 (s1)	Dataset 1: $y_{en,g1,s1}$	Dataset 3: $y_{fc,g1,s1}$
	I.D. (g2)	Set-up 1 (s1)	Dataset 2: $y_{en,g2,s1}$	Dataset 4: $y_{fc,g2,s1}$ (Output 1)
2			Computer Simulated Notch (cn),	EDM Notch (en)
	I.D. (g2)	Set-up 1 (s1)	Dataset 5: $y_{cn,g2,s1}$	Dataset 2: $y_{en,g2,s1}$
	I.D. (g2)	Set-up 2 (s2)	Dataset 6: $y_{cn,g2,s2}$	Dataset 7:$y_{en,g2,s2}$ (output 2)
		Set-up		
3			EDM Notch (en)	Fatigue Crack (fc)
	Plate Farside ($_{g1}$)	Set-up 1 (s1)	Dataset 1: $y_{en,g1,s1}$	Dataset 3: $y_{fc,g1,s1}$
	I.D. ($_{g2}$)	Set-up 2 (s2)	Dataset 7: $y_{en,g2,s2}$	Dataset 8: $y_{fc,g2,s2}$(output 3)

Examples of Dataset

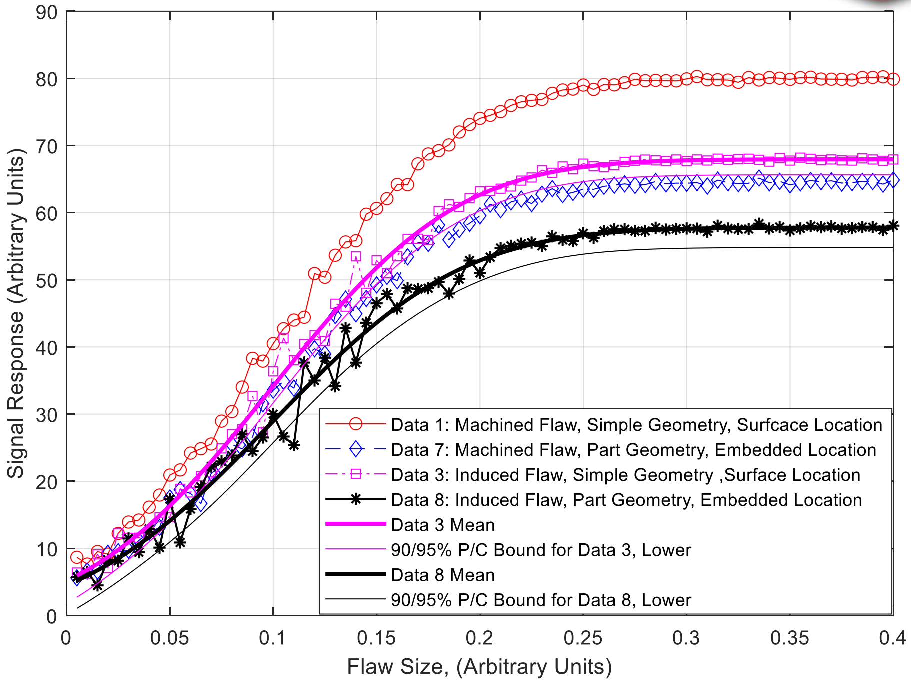


Following mean signal response relationship is assumed for Block 2,

$$\bar{y}_{e,2,2} = \frac{\bar{y}_{s,2,2}\bar{y}_{e,2,1}}{\bar{y}_{s,2,1}}. \quad (3)$$

The model assumes square root of the sum of squares formula for resulting standard deviation

$$\sigma^x_{e,2,2} \cong \sigma^x_{e,2,1} \quad (4)$$

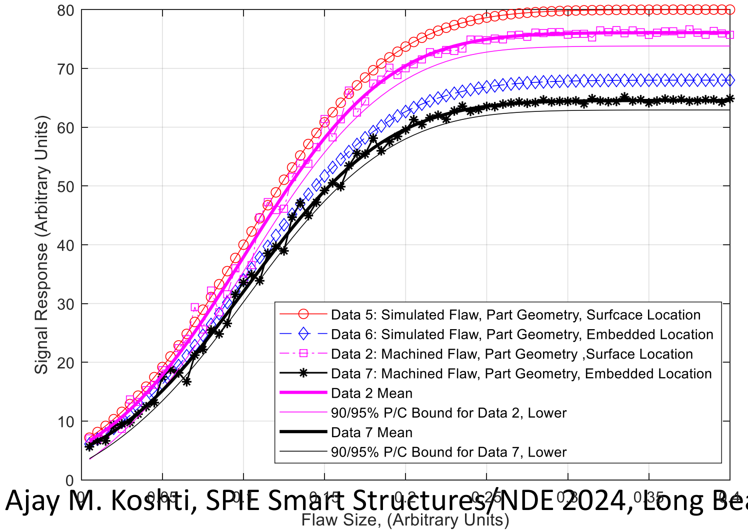


Following mean signal response relationship is assumed for Block 1,

$$\bar{y}_{c,2,1} = \frac{\bar{y}_{c,1,1}\bar{y}_{e,2,1}}{\bar{y}_{e,1,1}}, \quad (1)$$

where, $\bar{\ }$ is used to indicate mean value of dataset variable y at any given value of x. The model assumes square root of the sum of squares formula for resulting standard deviation,

$$\sigma^x_{c,2,1} = \sqrt{\left(\sigma^x_{c,1,1}\right)^2 + \left(\sigma^x_{e,2,1}\right)^2 + \left(\sigma^x_{e,1,1}\right)^2} \quad (2)$$



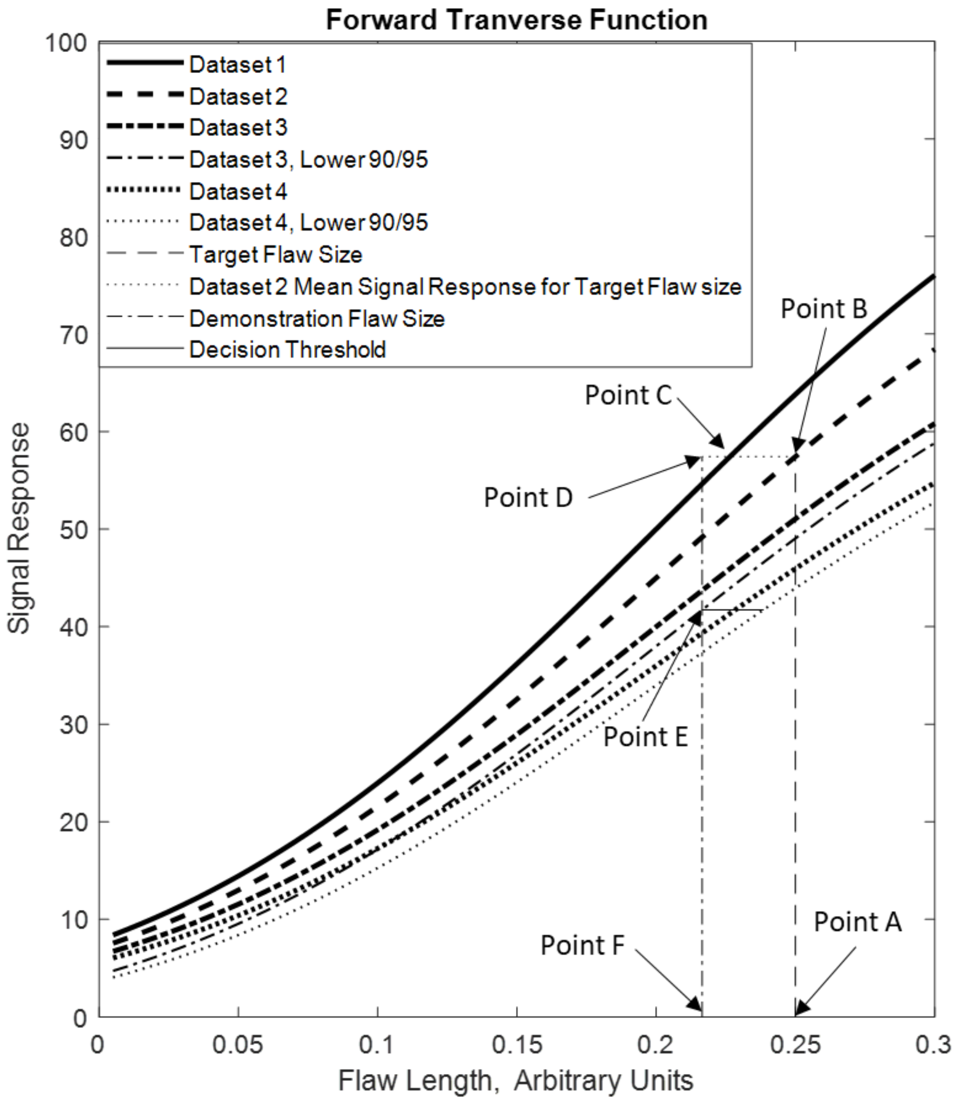
Following mean signal response relationship is assumed,

$$\bar{y}_{c,2,2} = \frac{\bar{y}_{c,1,1}\bar{y}_{e,2,2}}{\bar{y}_{e,1,1}} \quad (5)$$

The model assumes square root of the sum of squares formula for resulting standard deviation,

$$\sigma^x_{c,2,2} = \sqrt{\left(\sigma^x_{c,1,1}\right)^2 + \left(\sigma^x_{e,2,2}\right)^2 + \left(\sigma^x_{e,1,1}\right)^2} . \quad (6)$$

Sequence of Forward Transfer Function Calculation Steps



Steps from point A to F in alphabetical order

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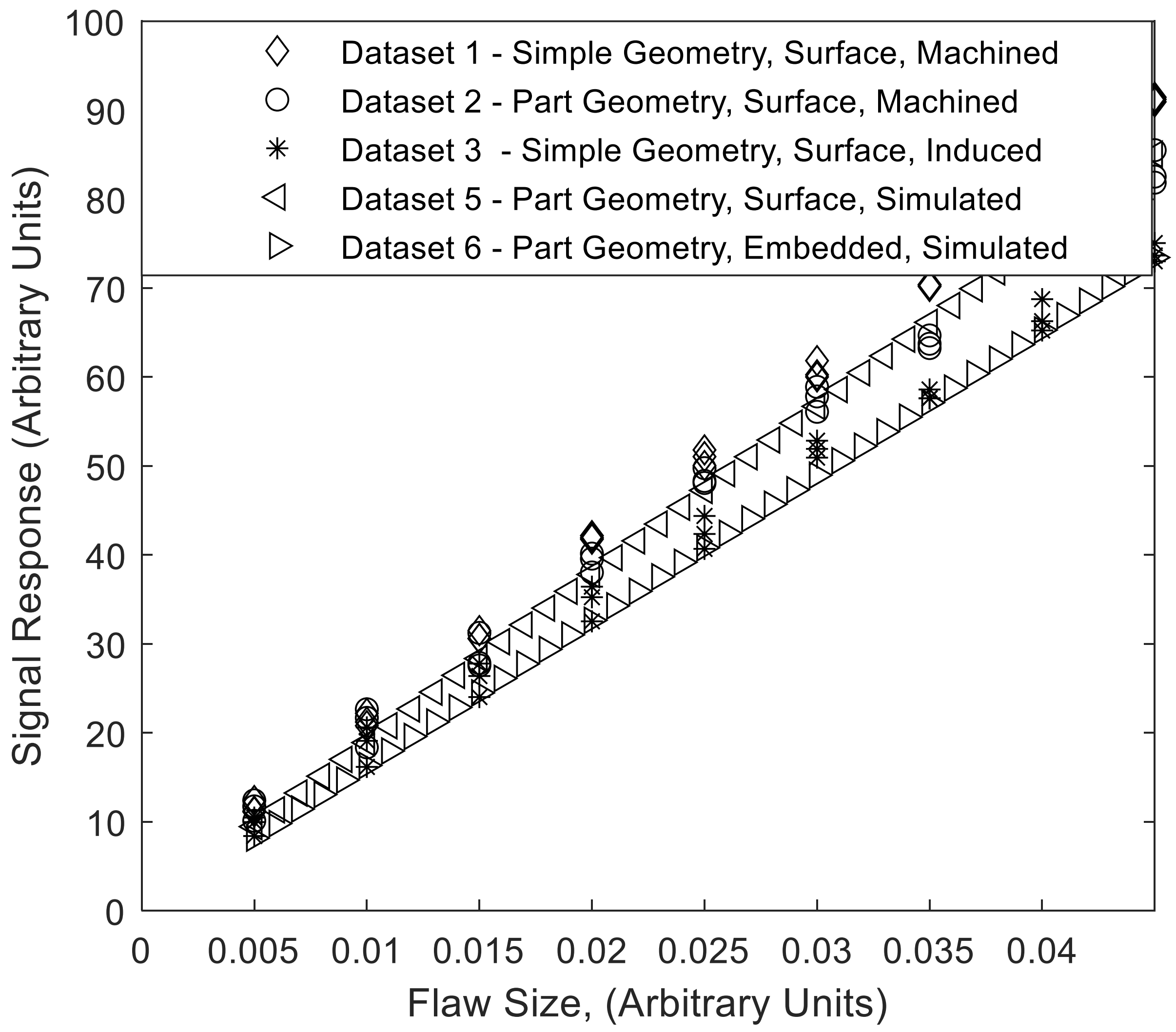
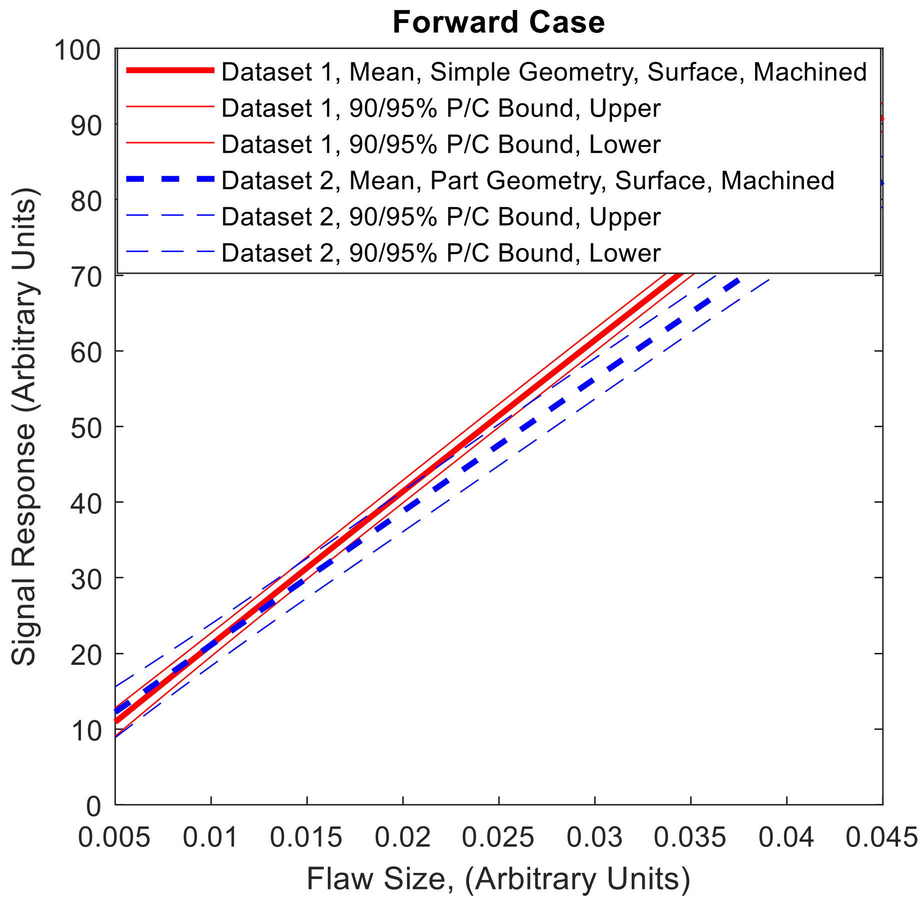
Transfer Function Example 1: Detection of Induced Embedded Flaw in Part Geometry

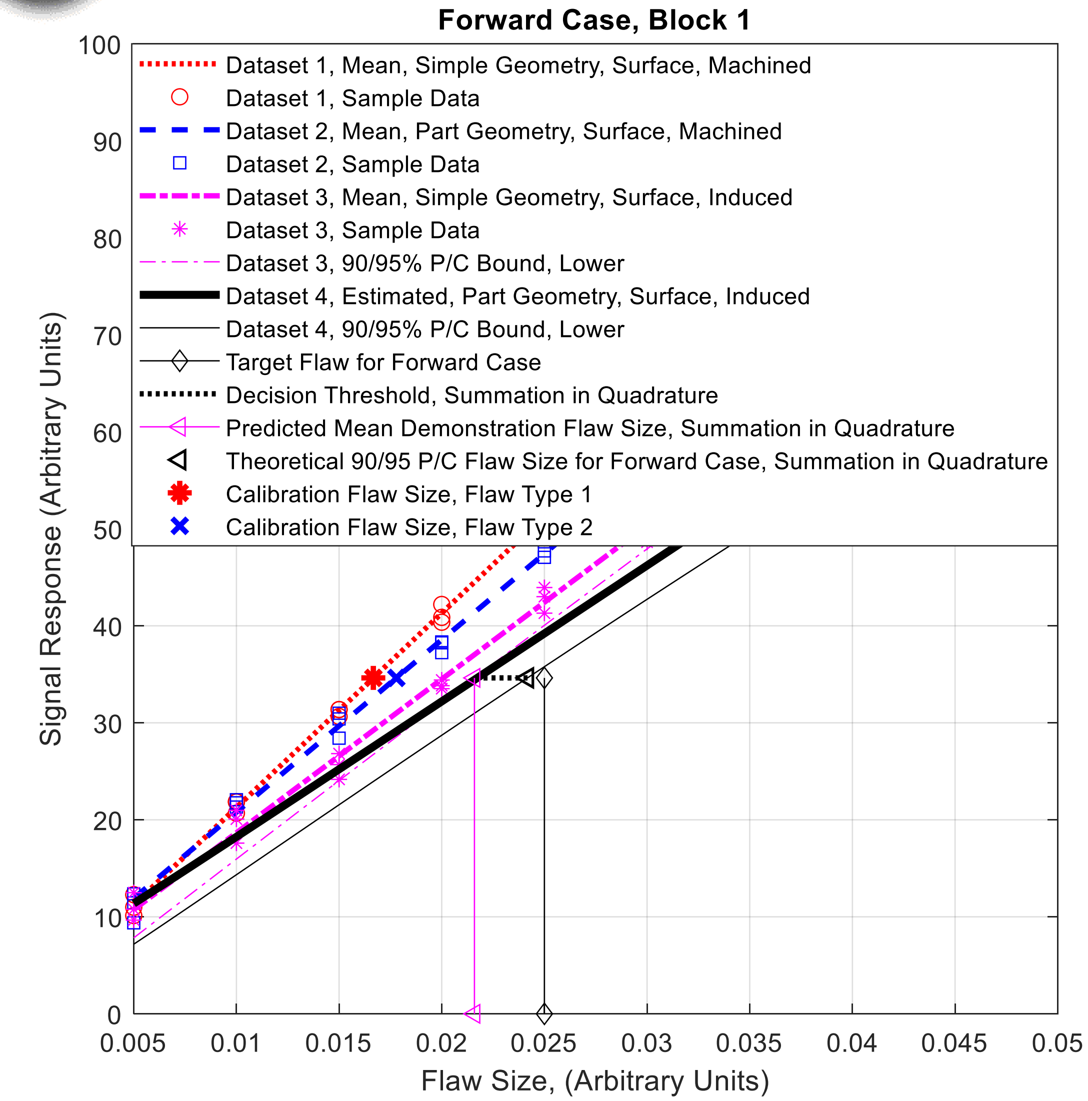


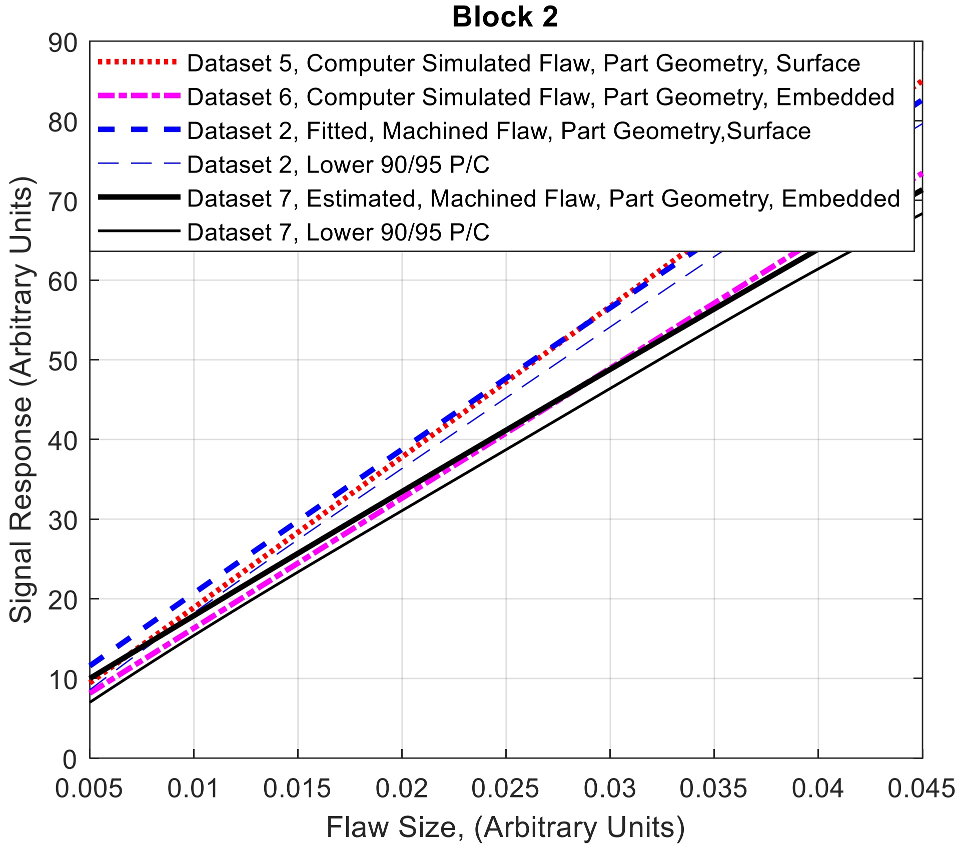
Example datasets



Fitted function plots for datasets 1 and 2

Transfer Function Example 1: Detection of Induced Embedded Flaw in Part Geometry



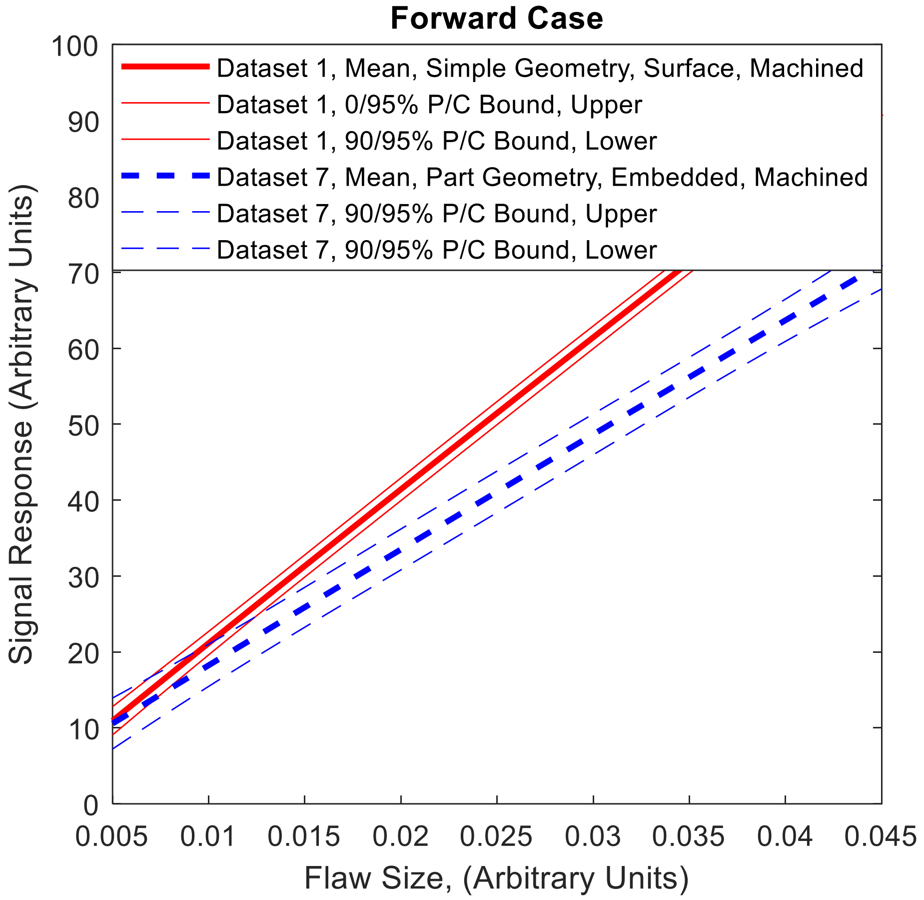


Block 2 fitted datasets

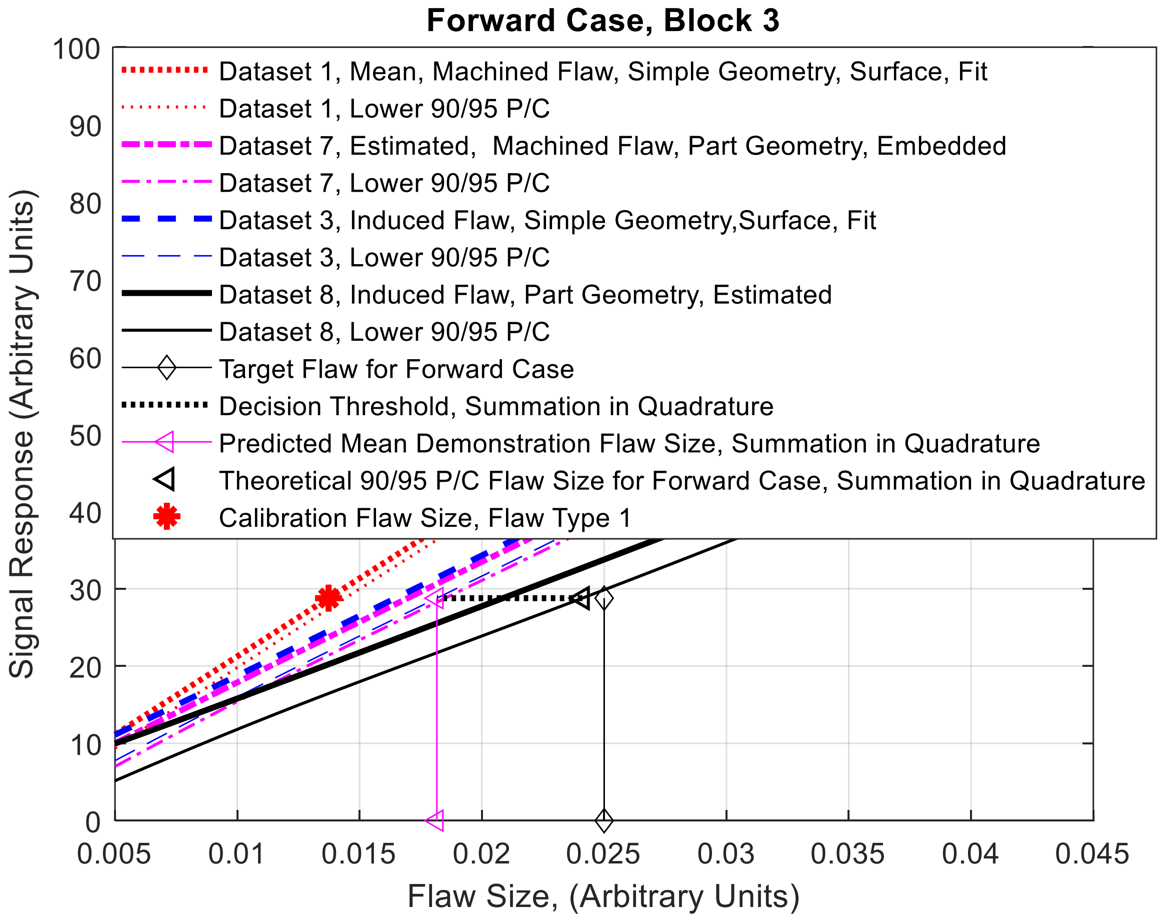
Example of forward case for Block 1

Flaw sizes within range of replicates for datasets 1, 2 and 3 (optional)

Transfer Function Example 1: Detection of Induced Embedded Flaw in Part Geometry



Fitted datasets 1 and 7 for Block 3



Forward case for Block 3

Noise Analysis

- There is a noise distribution corresponding to each empirical dataset.
- Noise distribution is affected by part geometry but also by the set-up.
- Threshold level noise level corresponding to probability of false positive (POF) denoted as $y_{crack}^{POF,1/95}$ (i.e., 1 %POF and 95% confidence) may be computed.
- Noise measurements should be in unflawed areas where flaw could occur.
- The decision threshold y_{crack}^{thr} should be greater than or equal to noise threshold and less than or equal to the 90/95 P/C signal level $y_{crack}^{POD,90/95}$.
- $y_{crack}^{POF,1/95} \leq y_{crack}^{thr} \leq y_{crack}^{POD,90/95}$.

Transfer Function Example 4: Detection of Induced I.D. Flaw

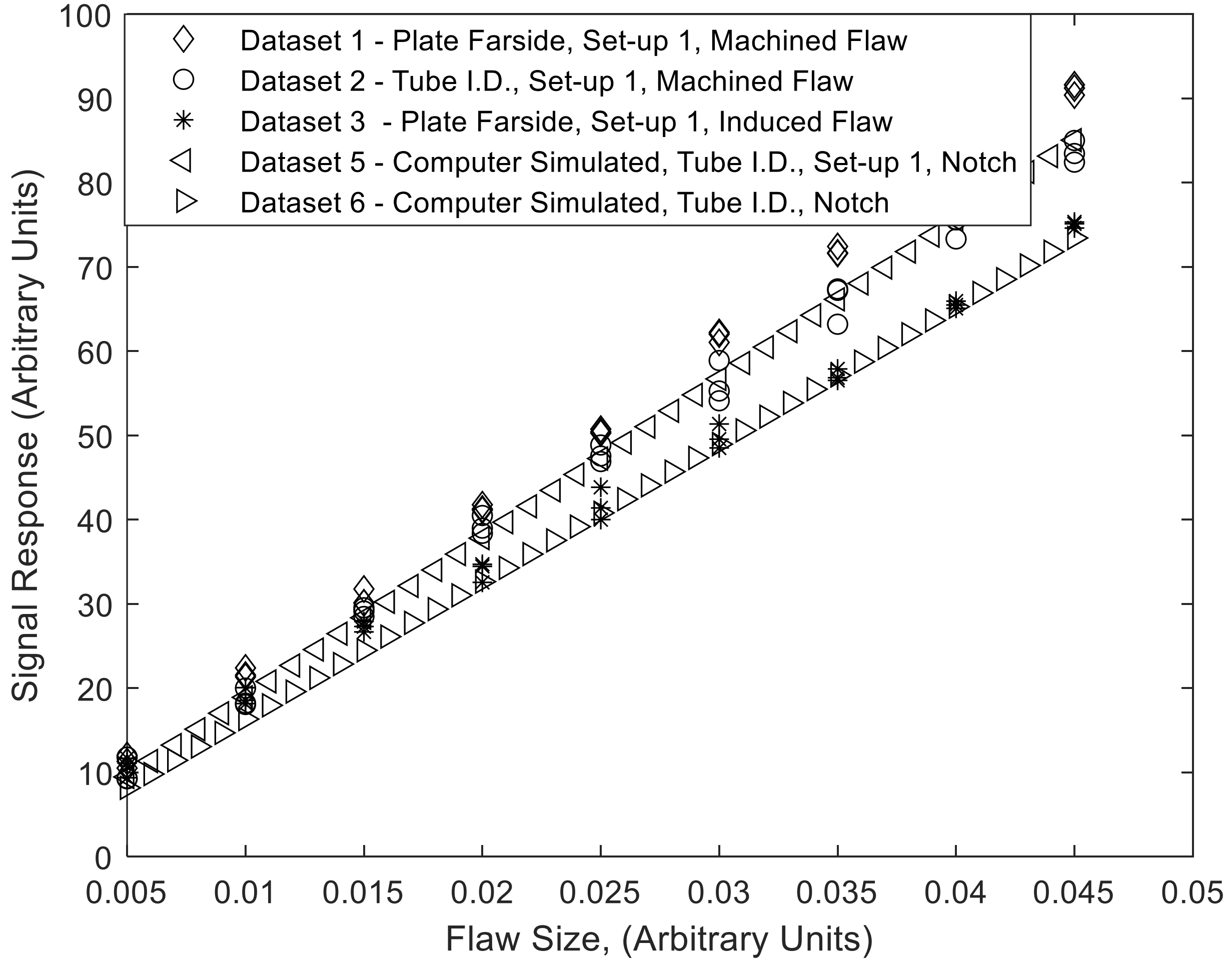
- Uses 2 setups in transfer function calculations.
- Set-up differences between reference standard or geometry transfer specimen and part
- Differences in electrical conductivity between reference standard and part cause differences in the set-up

Block	Location	Set-up	Flaw Type	
1			EDM Notch (en)	Fatigue Crack (fc)
	Plate Farside (g1)	Set-up 1 (s1)	Dataset 1: $y_{en,g1,s1}$	Dataset 3: $y_{fc,g1,s1}$
	I.D. (g2)	Set-up 1 (s1)	Dataset 2: $y_{en,g2,s1}$	Dataset 4: $y_{fc,g2,s1}$ (Output 1)
2			Computer Simulated Notch (cn),	EDM Notch (en)
	I.D. (g2)	Set-up 1 (s1)	Dataset 5: $y_{cn,g2,s1}$	Dataset 2: $y_{en,g2,s1}$
	I.D. (g2)	Set-up 2 (s2)	Dataset 6: $y_{cn,g2,s2}$	Dataset 7: $y_{en,g2,s2}$ (output 2)
		Set-up		
3			EDM Notch (en)	Fatigue Crack (fc)
	Plate Farside ($_{g1}$)	Set-up 1 (s1)	Dataset 1: $y_{en,g1,s1}$	Dataset 3: $y_{fc,g1,s1}$
	I.D. ($_{g2}$)	Set-up 2 (s2)	Dataset 7: $y_{en,g2,s2}$	Dataset 8: $y_{fc,g2,s2}$(output 3)

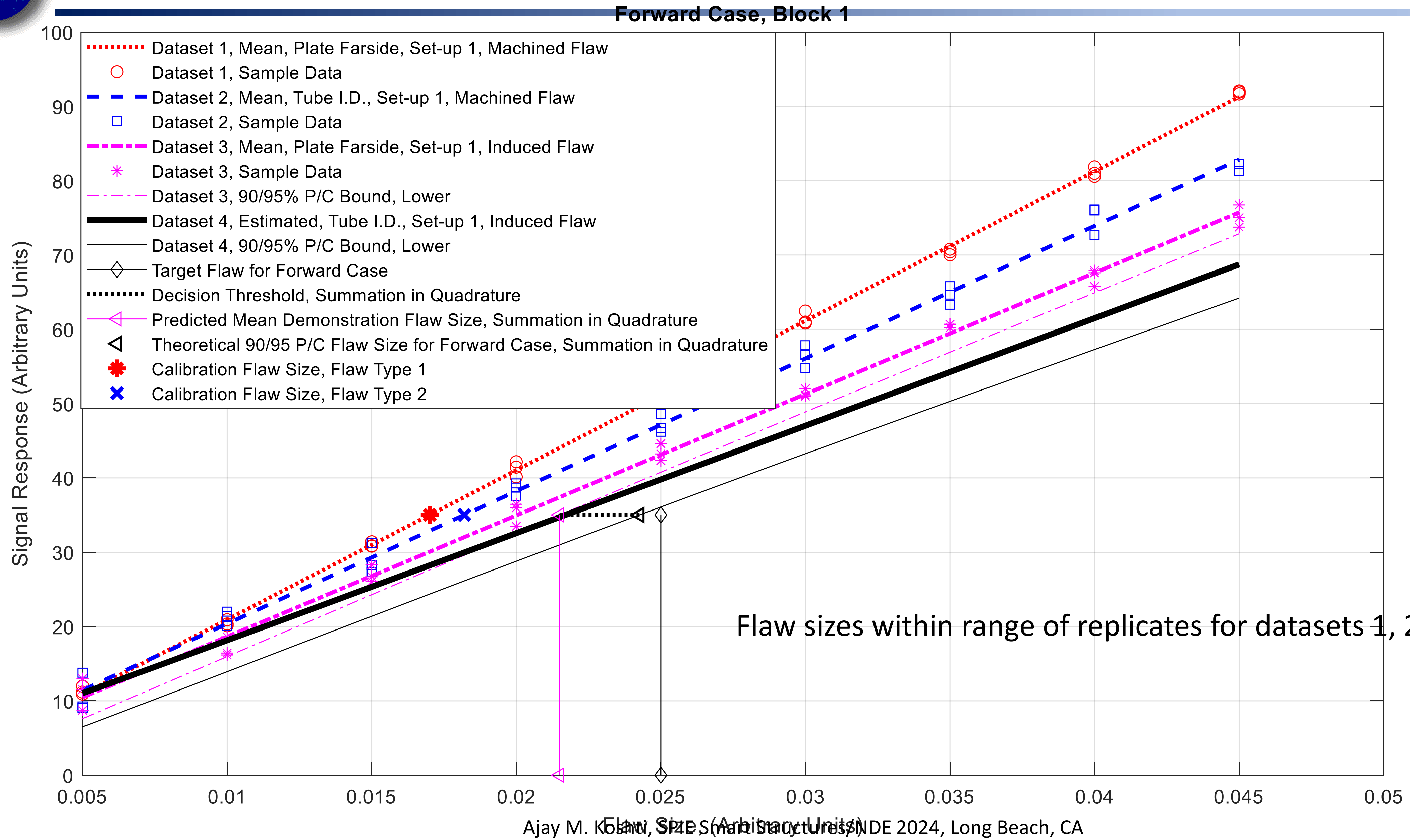
Option 1

- There are two options for use of Dataset 7.
  - In Option 1, Dataset 7 output from Block 2 is used as input for Block 3. Assumes that empirical Dataset 7 is not available.
  - In Option 2, Block 2 is not used. Dataset 7 is empirical data in Block 3.
- Option 2 is a case of using EDM notch to crack response transfer ratio obtained using set-up 1 for use in set-up 2.

Transfer Function Example 4: Detection of Induced I.D. Flaw

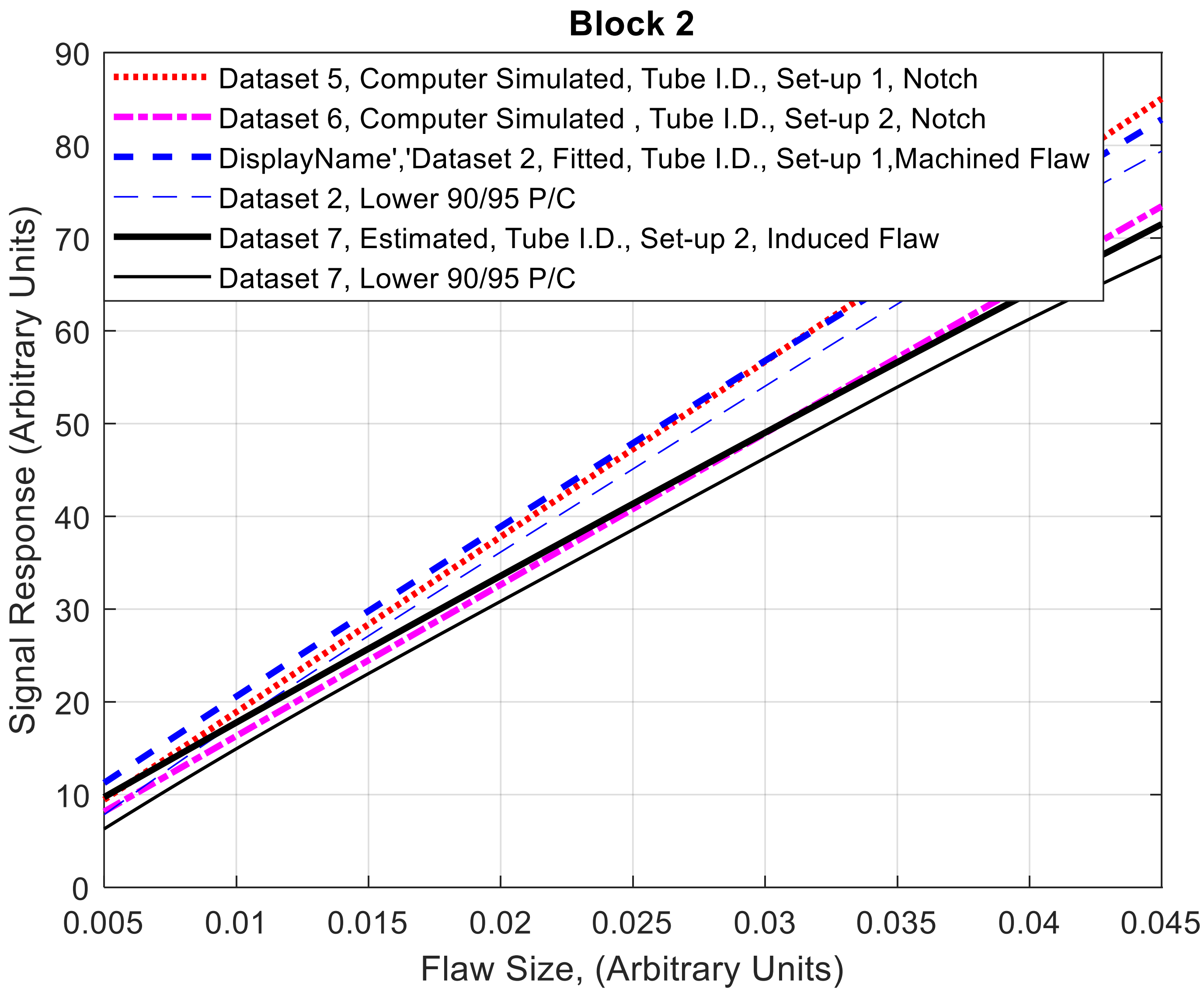


Example 4: Detection of Induced I.D. Flaw



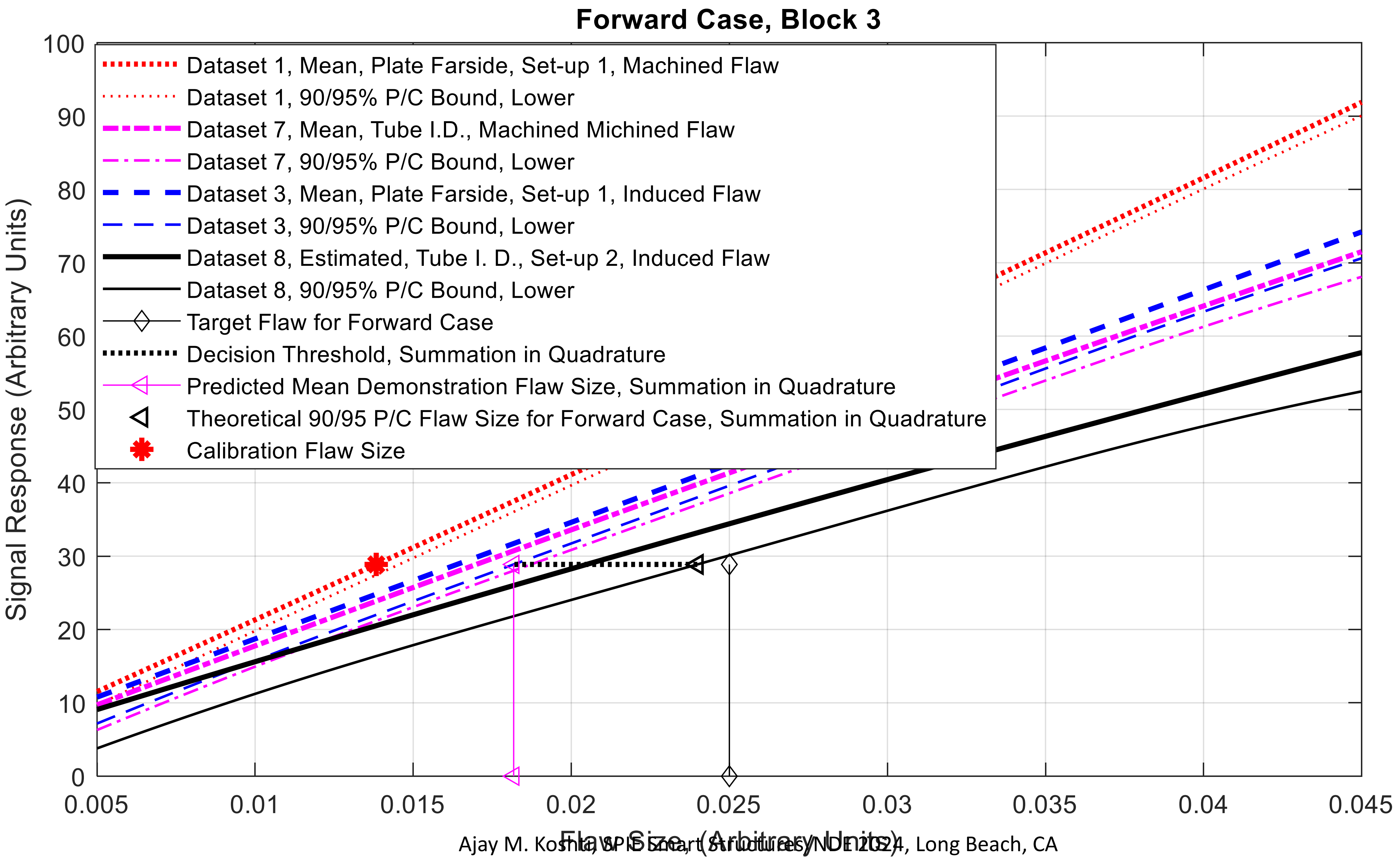
Flaw sizes within range of replicates for datasets 1, 2 and 3 (optional)

Transfer Function Example 4: Detection of Induced I.D. Flaw

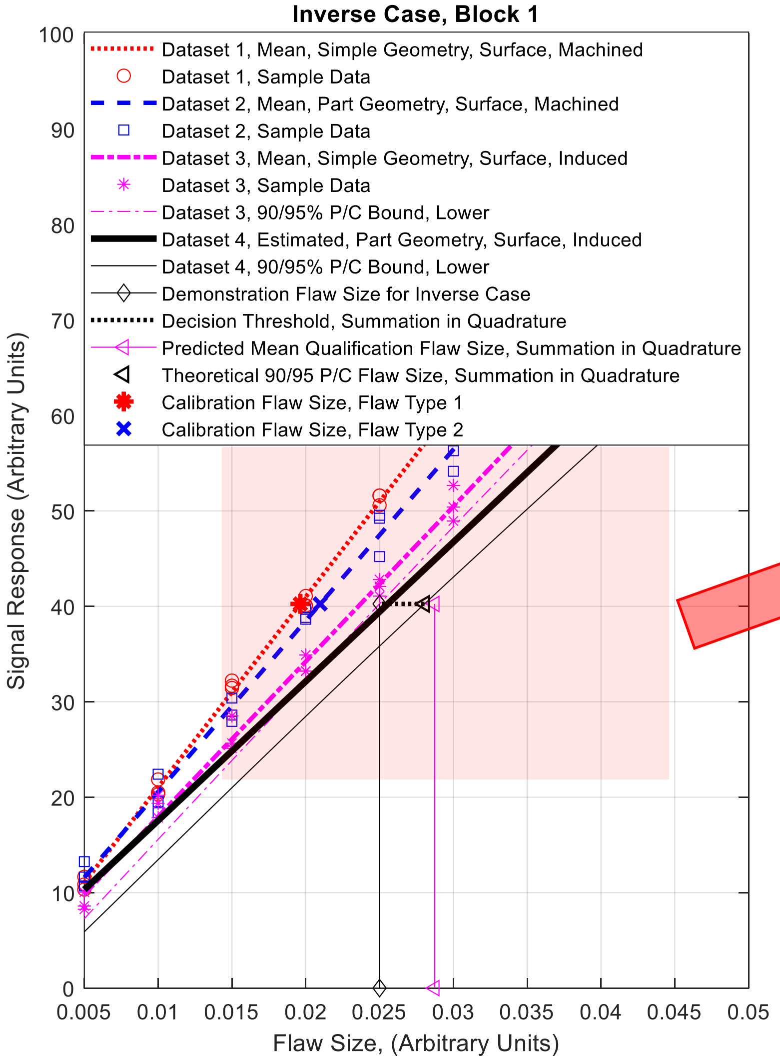


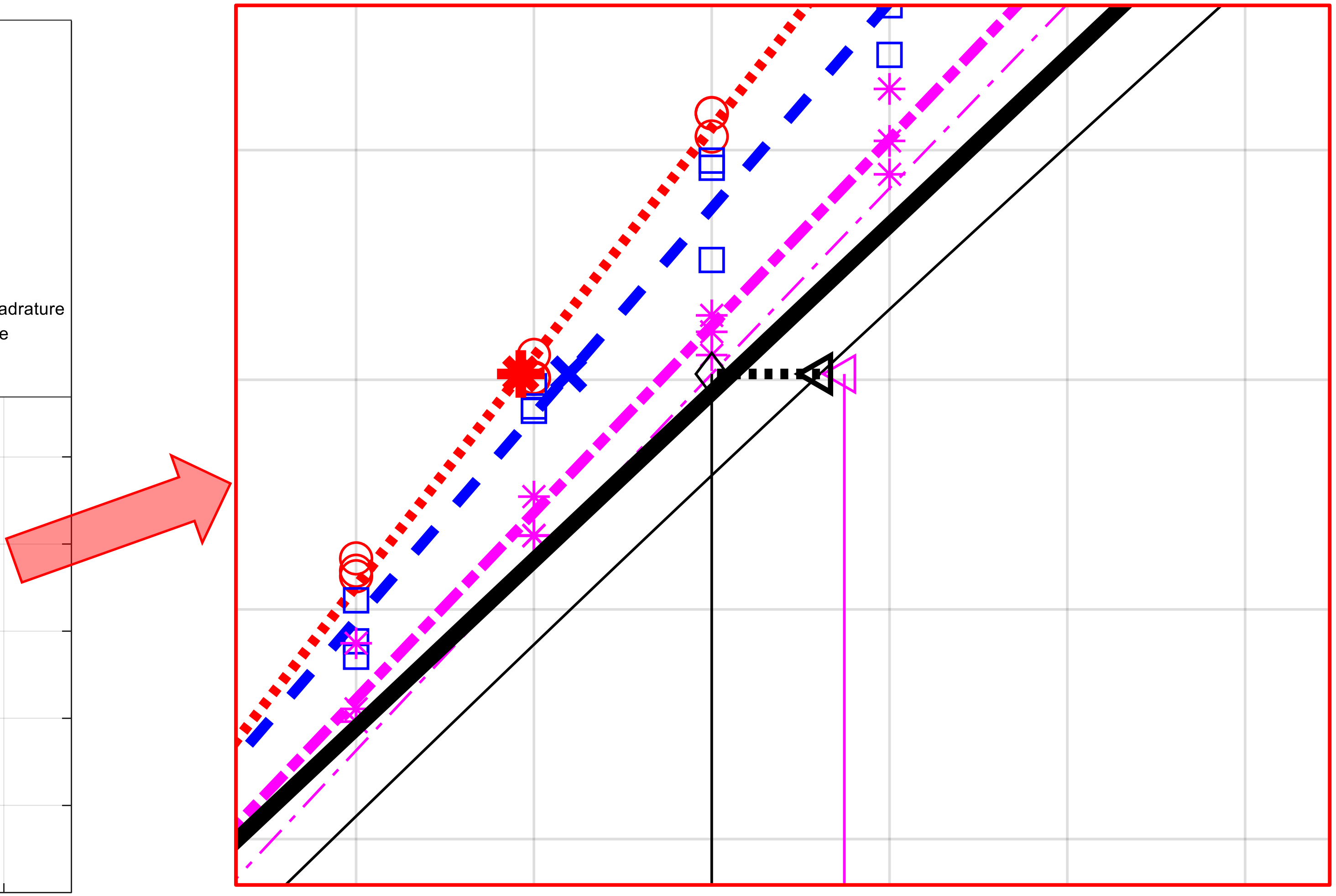
Option 1 uses transfer computed dataset 7

Example 4: Detection of Induced I.D. Flaw

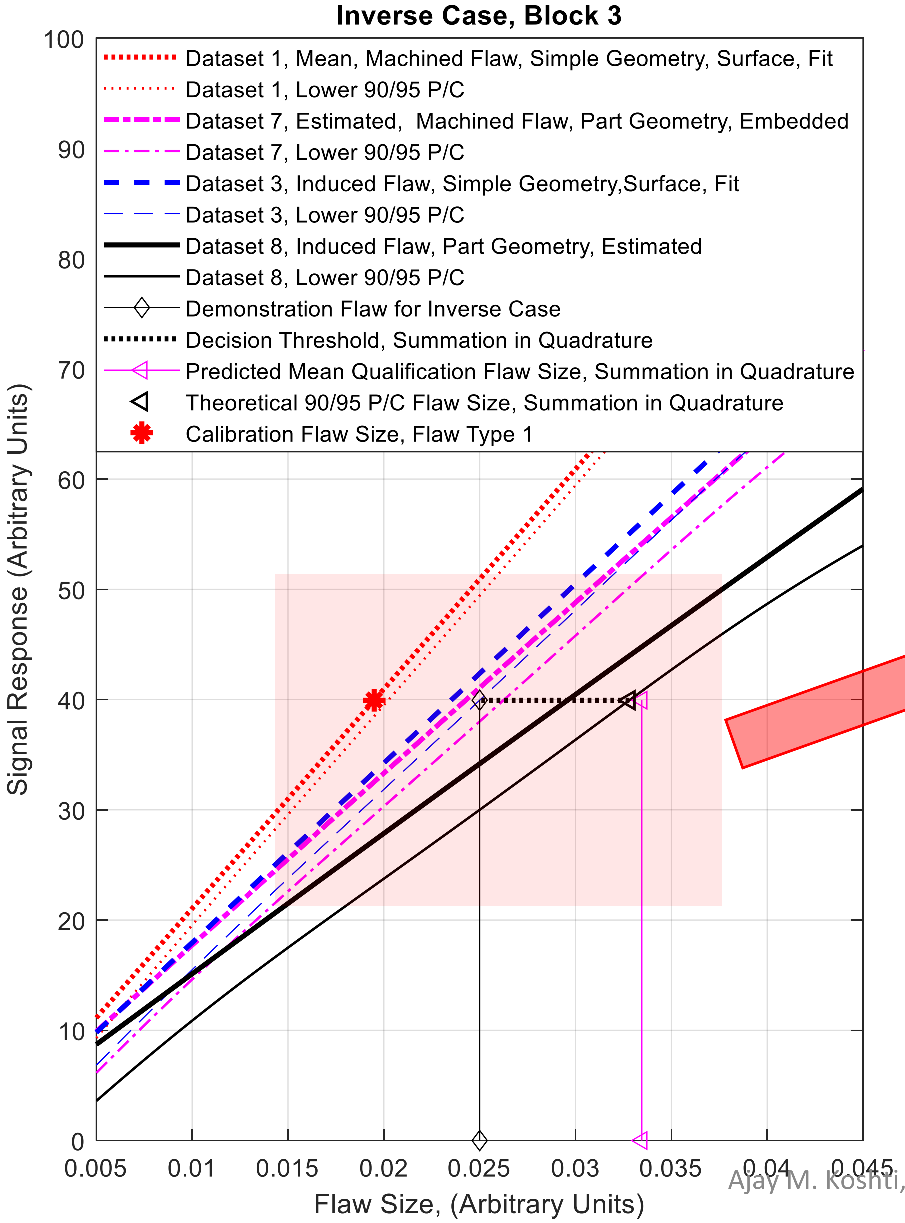


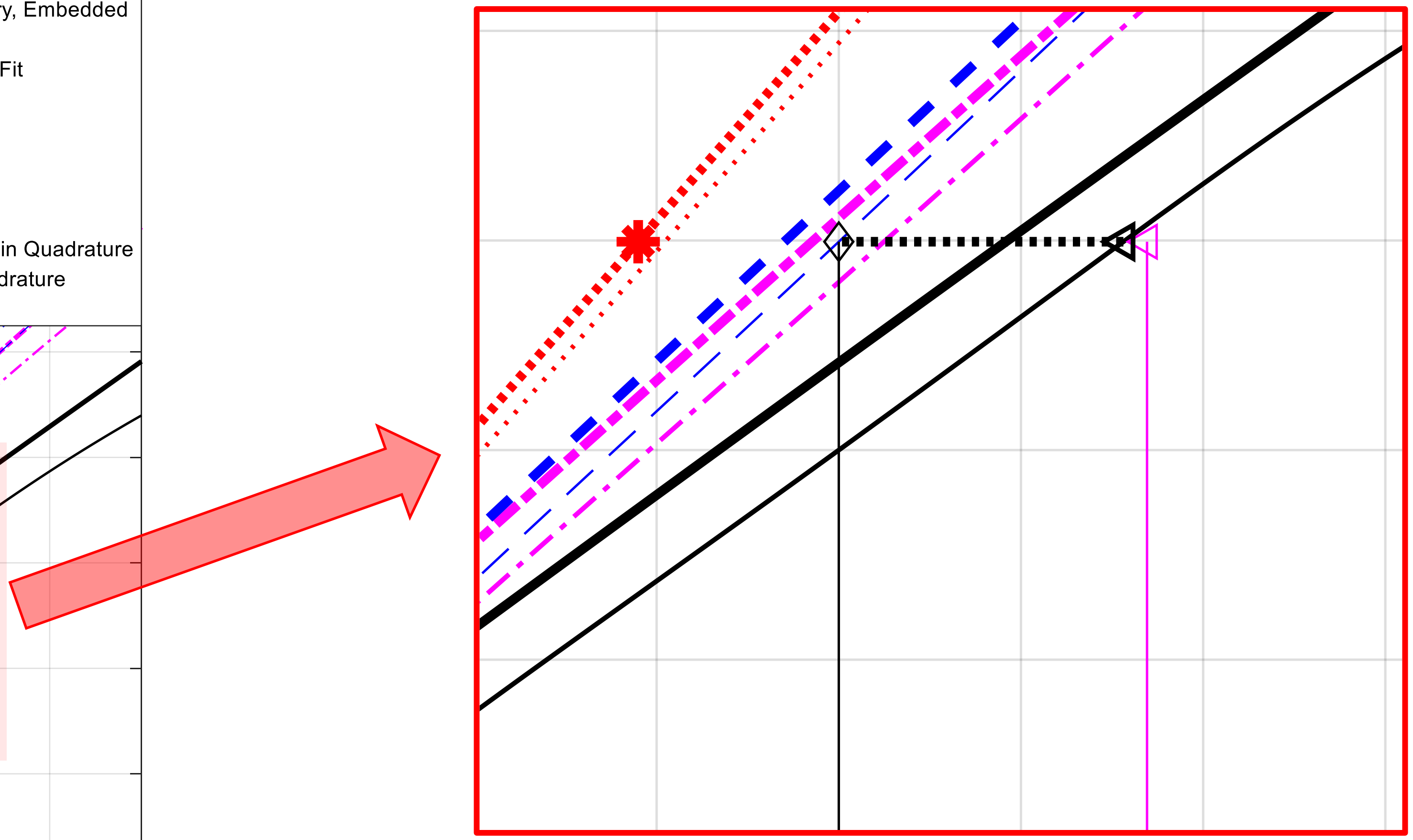
Example 1: Inverse Case, Block 1





Example 1: Inverse Case, Block 3





Conclusions

- The signal response transfer relationships model is devised first and then two step transfer function models have been devised for linear response signals with flaw size.
- The transfer function signal response relationships model provides relationship between these datasets towards estimating signal response from an embedded induced flaw.
- The transfer function model uses the signal relationships model to provide a model for calculating a signal decision threshold and corresponding 90/95% P/C flaw sizes.
- NDE procedure demonstration testing is performed on induced flaws in simple geometry specimens.
- An example of a transfer function NDE procedure qualification method for the forward and inverse cases is provided using simulated data.
- Besides Example 1, block definitions of three other two step transfer function applications are briefly discussed.
- Another transfer function case, described as the inverse case, calculates the target flaw size using a given demonstration flaw size.
- Since, transfer function approach assumes signal relationships model, it is a risk assessment or indirect POD assessment approach. Both the signal response transfer relationships model and the transfer function model are important in managing risk in results provided by the transfer function NDE technique qualification or assessment.
- The signal response relationships model needs to be validated with empirical and simulation data and then transfer function model needs to be validated for desired P/C on case-by-case basis. If non-linearity is seen in the sampled data, a transfer function simulation method can be used to assess applicability and confidence in the transfer function method.