Competitive Academic Agreement Program

Proactive and Hybrid Sensing based Inline Pipeline Defects Diagnosis and Prognosis

Dr. Yiming Deng (CU) and Dr. Yongming Liu (ASU)

11/10/2015

Main Objectives

This project developed a new form of sensing technique for emerging plastic piping materials, near-field microwave microscopic (NFMM) imaging method to identify and characterize injurious pipe body proactively with superior resolution and high sensitivity.

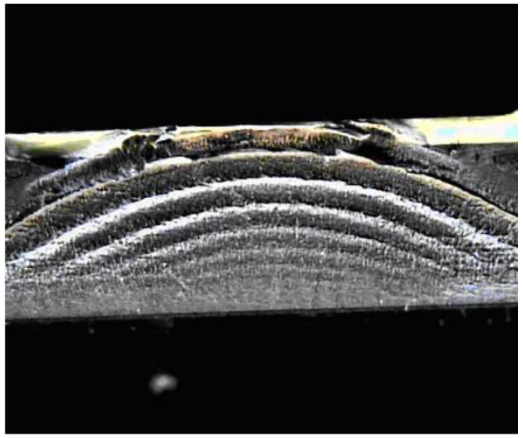
Diagnosis: find existing damage in emerging plastics at the earliest stage before it becomes failure critical

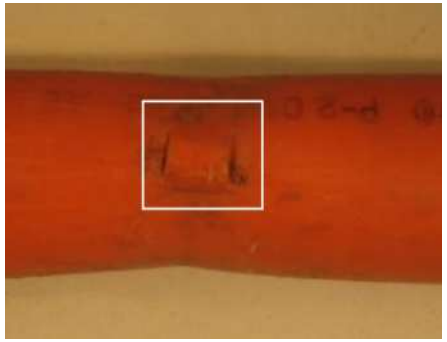
This project resulted in an information framework integrating the residual strength calculation, uncertainty quantification and propagation analysis using a Bayesian updating process to advance pipeline reliability evaluation and risk assessment tool.

Prognosis: accurately predict the remaining strength and propagation analysis for pipelining components

Motivations

- Types of failure [1]
  - Rock impingement induced cracking
  - Force fracture of joints
  - Improper squeezing induced failure
  - Welding location leaking
- Crack propagation





[1] Julie Maupin, Michael Mamoun. Plastic Pipe Failure, Risk, and Threat Analysis, DOT Project# 194, Contract Number: DTPH56-06-T-0004, GTI Report, 2009.

Project Team & Other Sponsors

- Dr. Yiming Deng (PI) and Dr. Yongming Liu (Institutional PI)

- CU Team: Xiaoye Chen (PhD), Salem Egdaire (PhD), Jarvis Hill (MS), Mohand Alzuhiri (MS), Abdusamea Elfaid (MS), Yangoubo Liu (MS), Xiaodong Shi (MS), Cheng Peng (MS), Samir Hashem (BS), Ngoc Duong (BS)
- ASU Team: Tishun Peng (PhD), Qinan Chang (PhD), Vishal Chandrasekhar, (MS), Varun Desai (MS), Rohan Cota (MS), Yuhao Wang (MS), Sahil Jain (MS), Namitha Ganapa (MS), Rolie Lodes (BS), Andrew Park (BS)

- Industry Collaborators: Alicia Farag, **Gas Technology Institute**; Eric Gamache, Brandon Babe, **Arkema Inc.**

University of Colorado
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Arizona State University

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Project Results - 1

Task 1: Develop multi-physics model for material loss defects detection – **Accomplished**

Task 2: Multi-resolution system prototype development - **Accomplished**, additional tasks proposed and being investigated

Task 3: Probabilistic prognosis and risk assessment for decision making – **Accomplished**

Task 4: Final report and internet based presentation - **Final report delivery on schedule (12/31/2015)**

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Project Results - 2

- The PI's model of integrating the pipeline safety research, educational and outreach goals within the CAAP frame is shown below which includes five key components: (1) unmet pipeline safety needs; (2) engineering (sensor technology, material, chemical, electronic and software technology); (3) market; (4) regulations (US DOT) and (5) innovative solutions.

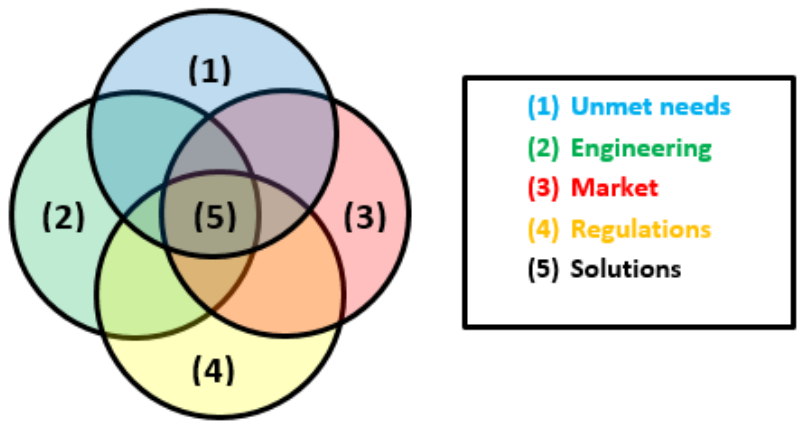


Fig. 1. Integration of pipeline safety research, educational goals in CAAP "Team-Approach" Model

Project Results - 3

- CU and ASU has implemented a "**team-approach**" and "**hierarchical team structure**" to have different levels of research and training activities among PhD, MS, and undergraduate students.
- The CAAP students supported by this CAAP research were heavily exposed to reliability and engineering design topics for emerging pipeline R&D technologies
- The CAAP students have actively participated national, international conferences and university-wide research symposiums, e.g. ASNT research symposium, Electromagnetic Nondestructive Evaluation Workshop, and RaCAS at CU.
- Two CAAP PhD students won the prestigious ASNT Research Symposium Student Awards in 2014 and 2015.

Other Project Results

- PhD (4), MS (12), BS (4)*
- 1 journal paper (ACI journal) and 5 conference papers (SAMPE, ENDE, ASNT) published. 2 journal papers and 2 conference papers to be submitted*
- One U.S. Patent in the pipeline (working with CU TTO)*
- Number of full employments: 3. More CAAP students to be graduated in 2016*
- Collaborative project: "Slow Crack Growth Evaluation of Vintage Polyethylene Pipes" funded by PHMSA's core R&D Program

* R&D Program performance metrics reported to Congress

Summary: Accomplishments - 1

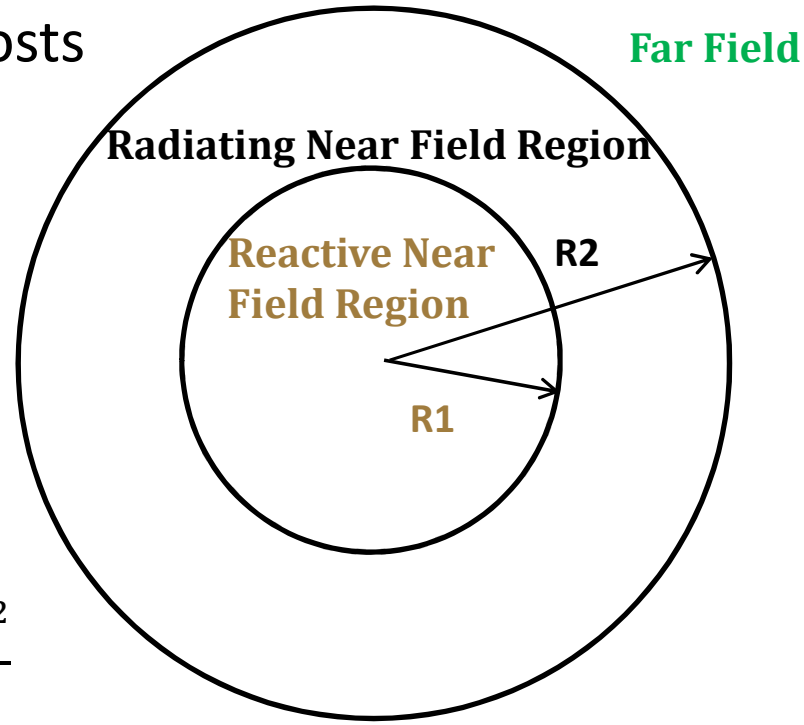
- A new form of NFMM sensing technique and diagnosis framework was developed at LEAP, CU-Denver assisted with multi-physics modeling. Both amplitude and phase information of the measured signals have been successfully exacted.
- Different piping materials (and more) have been studied, e.g. PA, metal, HDPE, CFRP, GFRP samples
- System optimization significantly improve the imaging capability: Sub-mm spatial resolution is accomplished; micron-scale is being investigated.
- High-fidelity 3D Numerical Model has been developed.

Summary: Accomplishments - 2

- Compressed Sensing method successfully applied to piping materials NDE imaging.
- Sparse sampling of NFMM signal completes the desire of lesser data size and scanning time.
- Estimated signal shows high fidelity and adequate data SNR comparing with original signal. Quality estimation from even lesser percentage of samples is under review. (single pixel microwave imaging technique? Digital micro-mirror device)
- Dictionary learning algorithms could be used to more efficiently and sparsely represent the signal.

Near Field Microwave Microscopy

- Nondestructive, low power, low costs
- Noncontact and contact mode
- High contrast, high spatial resolution (sub-mm and beyond)
- Used in characterizing materials
- behaviors and microstructures

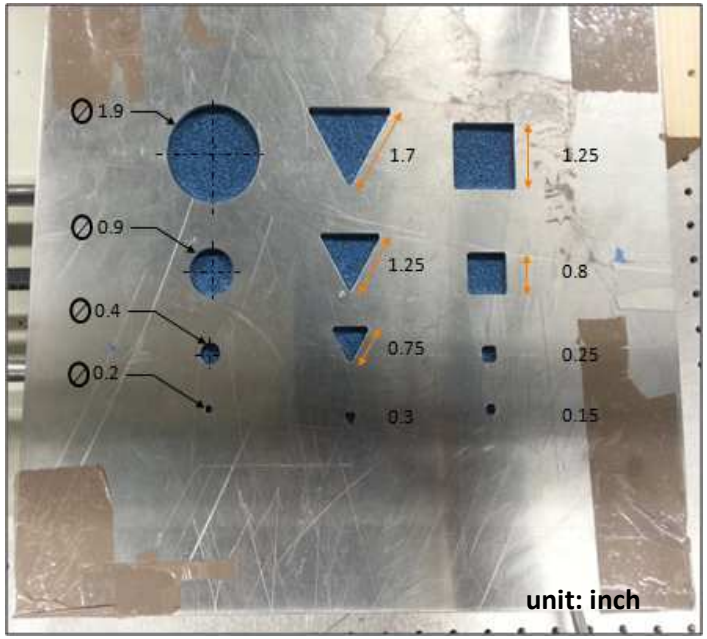


$$R_1 = 0.62\sqrt{\frac{D^3}{\lambda}} \qquad R_2 = \frac{2D^2}{\lambda}$$

- D is the maximum linear dimension of the sensor tip
- λ is the radiation wavelength of the input signal

Imaging Calibration Materials

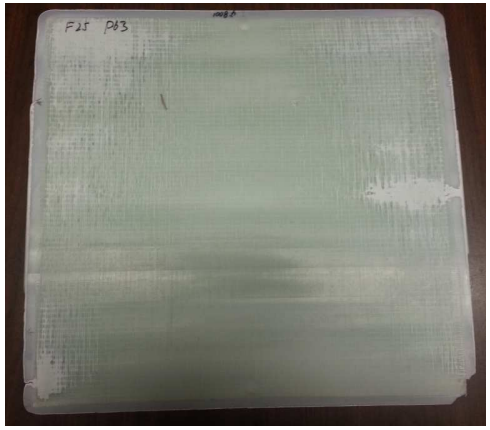
Aluminum Sample



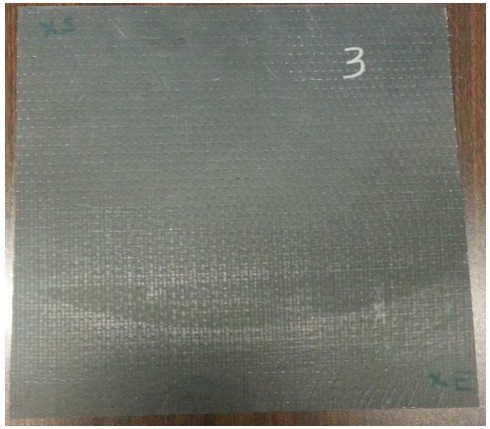
Concrete Sample

In collaboration with Civil and Environmental Engineering Department

Piping Materials at LEAP



(a)



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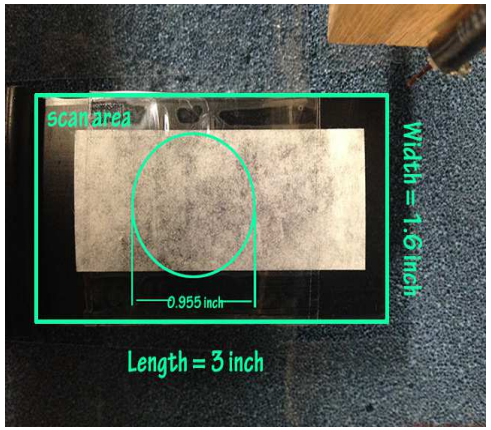

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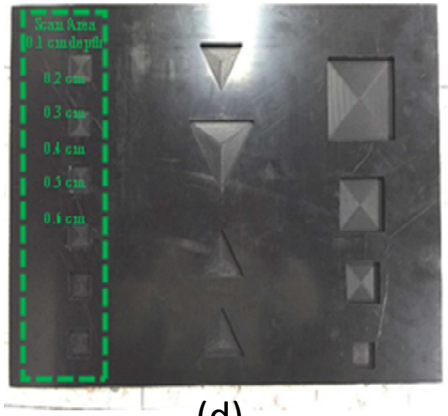
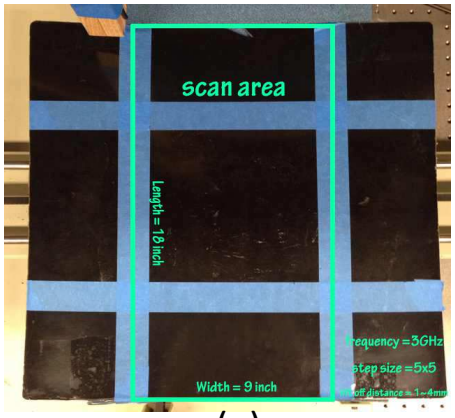


(d)



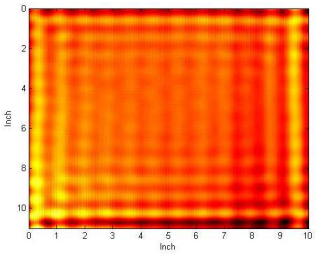
(e)

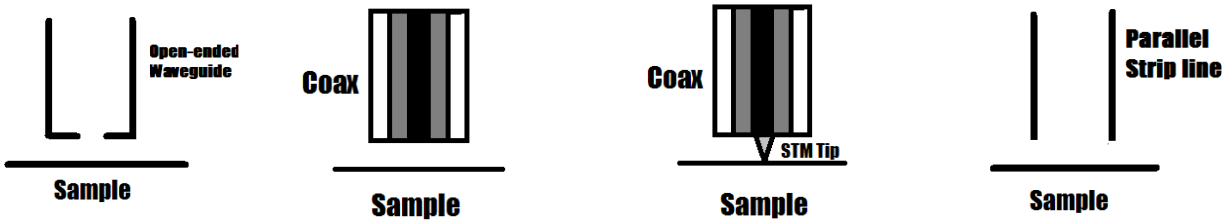
(a) PA – 6 (b) CFRP Sample (c) HDPE Pipe (d) PE Sample (e) GFRP Sample

NFMM Sensor Development

- Microwaves impinging on the sample drive an effective field on both inside and outside the sample: surface and subsurface image
- To extract the reflected microwave, a special probe-tip is needed that only sensitive to high spatial frequency components.
- There are several different sensors have been developed in our LEAP group for NFMM to improve the image resolution and sensitivity.

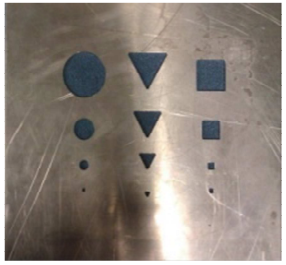
"blank scan"

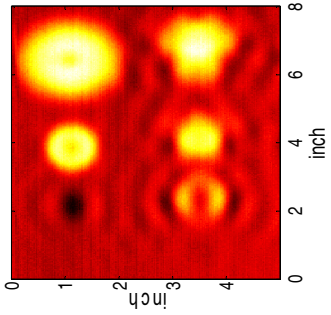




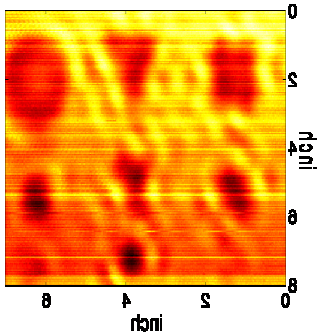
Anlage et al., scanning probe microscopy, 2007

NFMM Sensor Development





(a)



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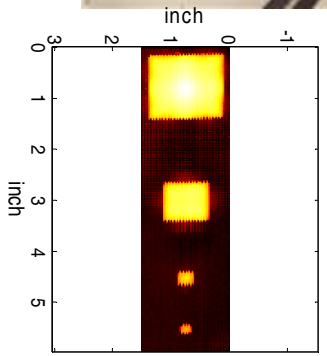
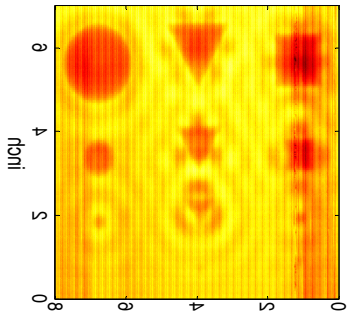


(c)

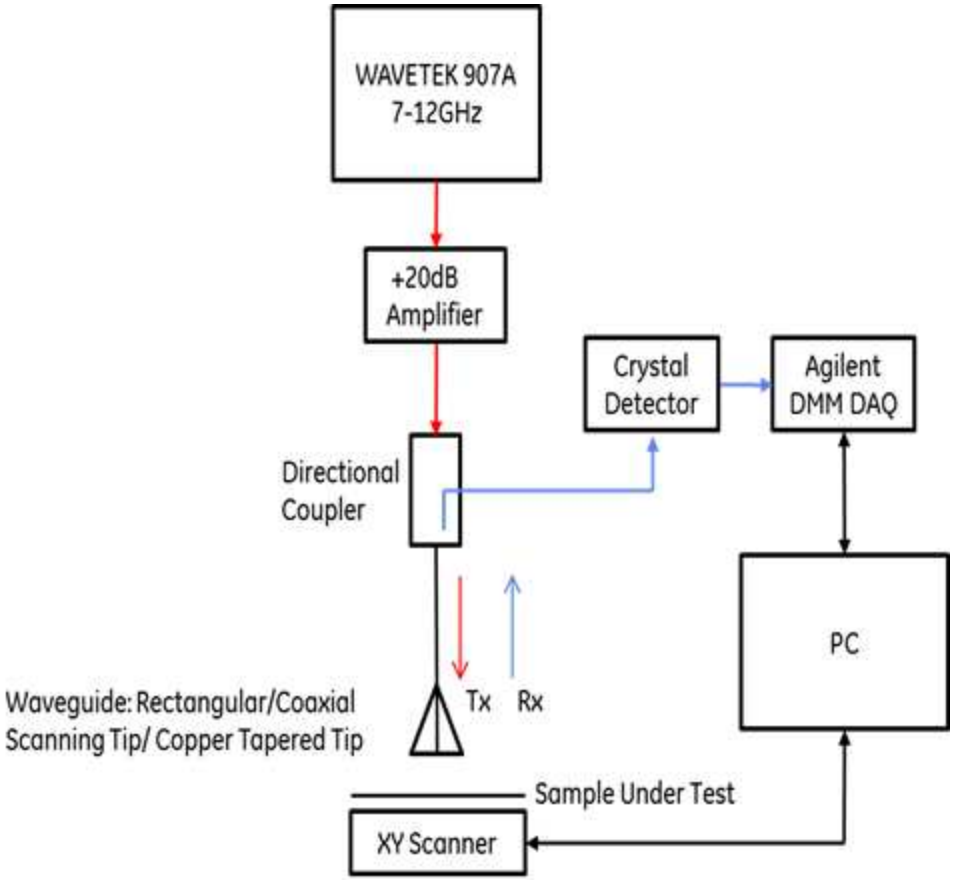


(d)

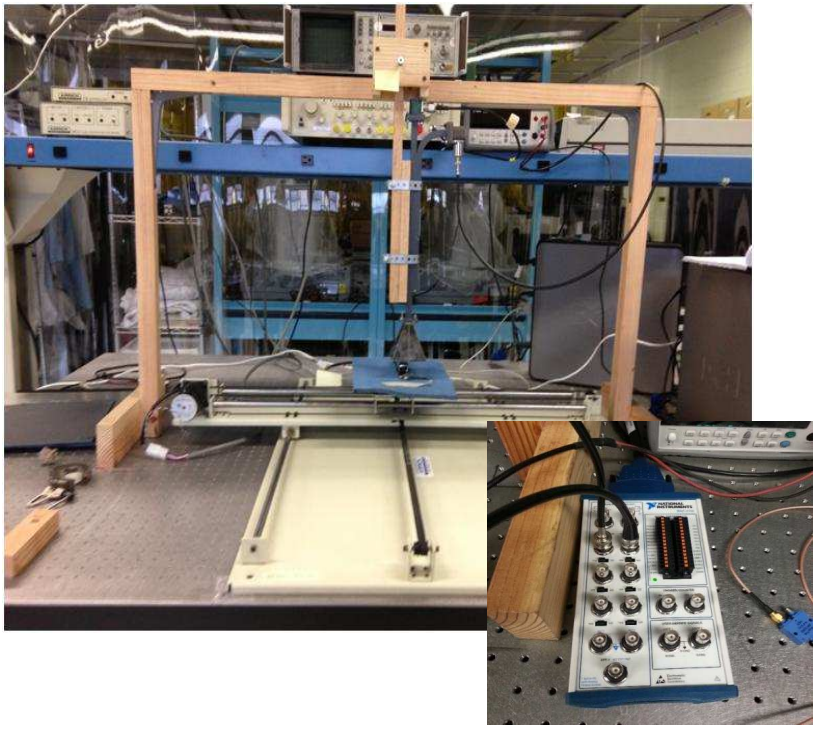
(e)

(a) Open-Ended Waveguide (b) Narrow Resonant Slit (c) Coaxial-Tip Antenna (d) Copper-SMA Probe Tip (e) Multi-Channel NFMM Sensor

Amplitude Imaging Approach

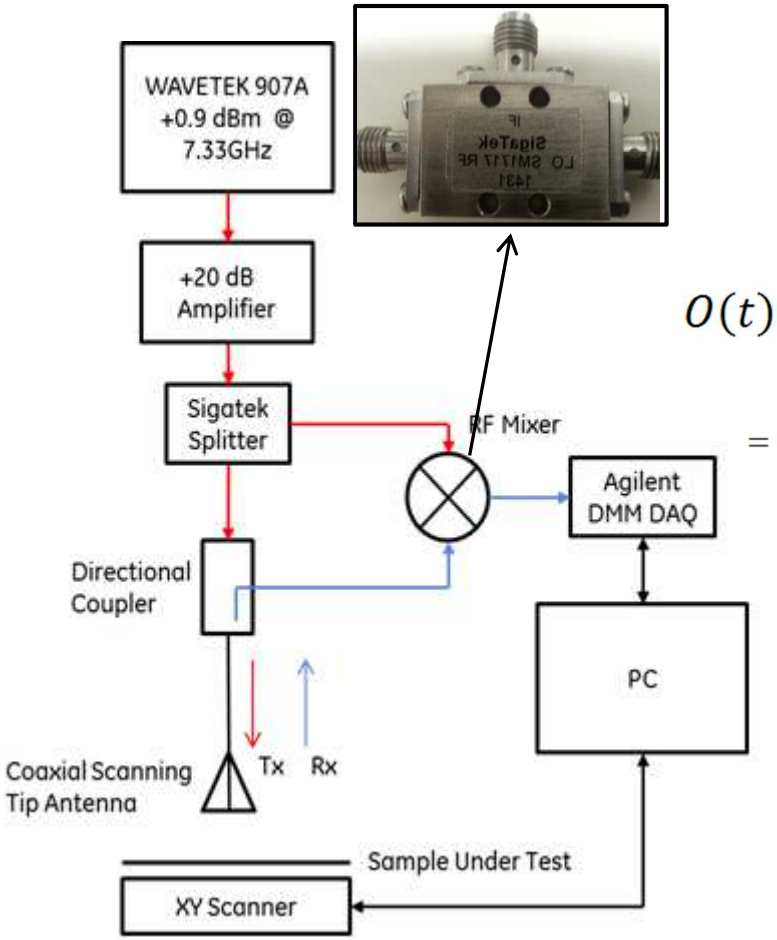


NFMM-AMP Design Schematic

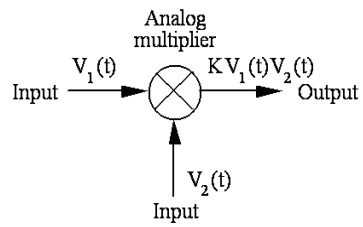


NFMM Amplitude Imaging Experiment Setup

Phase Imaging Approach: Demodulation



NFMM-PHASE Design Schematic



$$O(t) = \frac{A_1 A_2}{2}[\cos(w_1 t + w_2 t - \Phi) + \cos(w_1 t - w_2 t + \Phi)$$

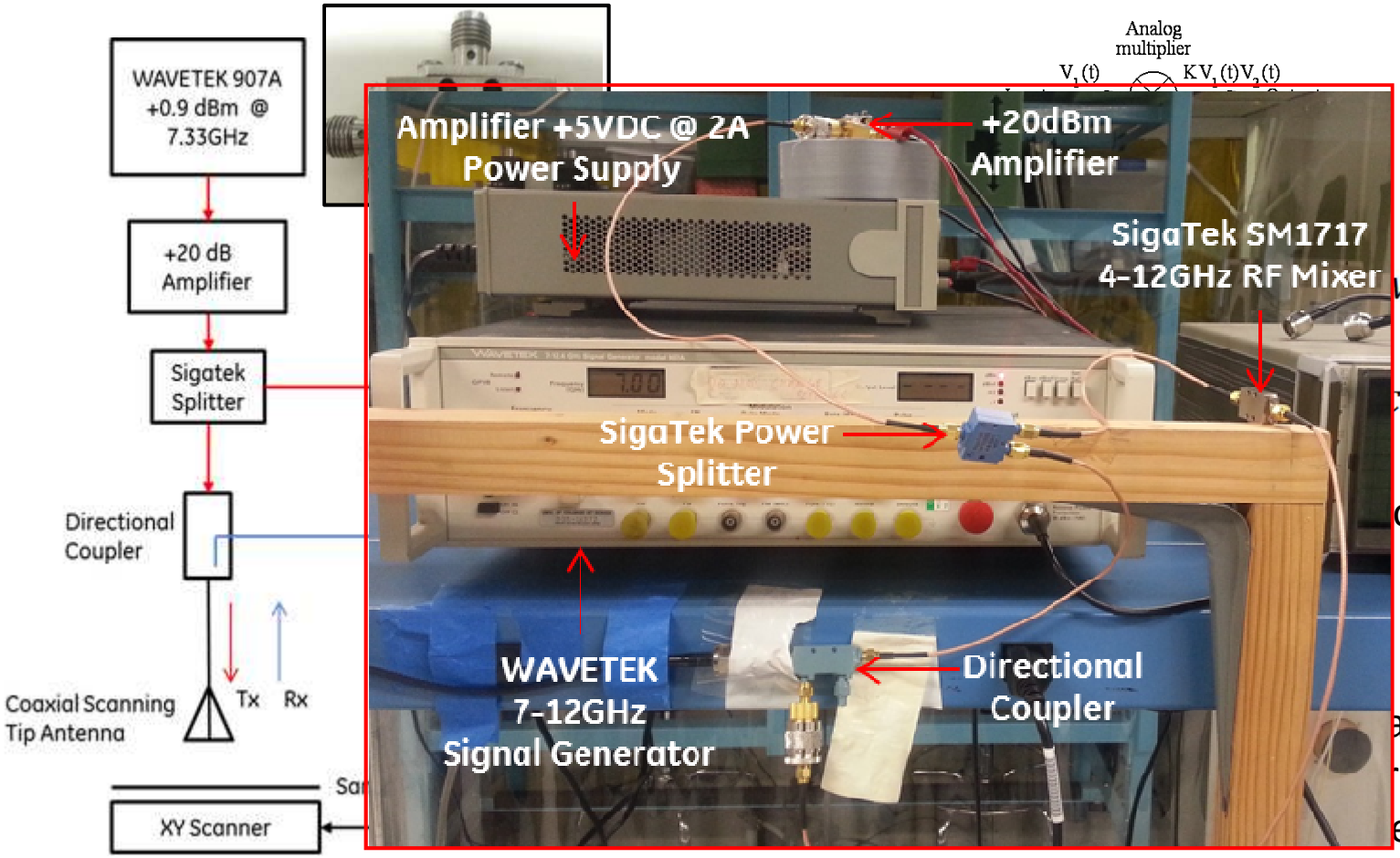
$$= \frac{k\, A_1 A_2}{2}\left[cos\left(2 * \pi * 20x10^9 * t\right) + cos(\Phi)\right]$$

- Mixing is non-linear operation so O(t) has harmonics of input signals

$$mf_1 \pm nf_2$$

- Real-world O(t) contains a fundamental freq and a # of sum and diff. harmonics
- Usually interested in one freq, rest are filtered out

Phase Imaging Approach: Demodulation



$w_1 t - w_2 t + \Phi)$

$cos(\Phi)]$

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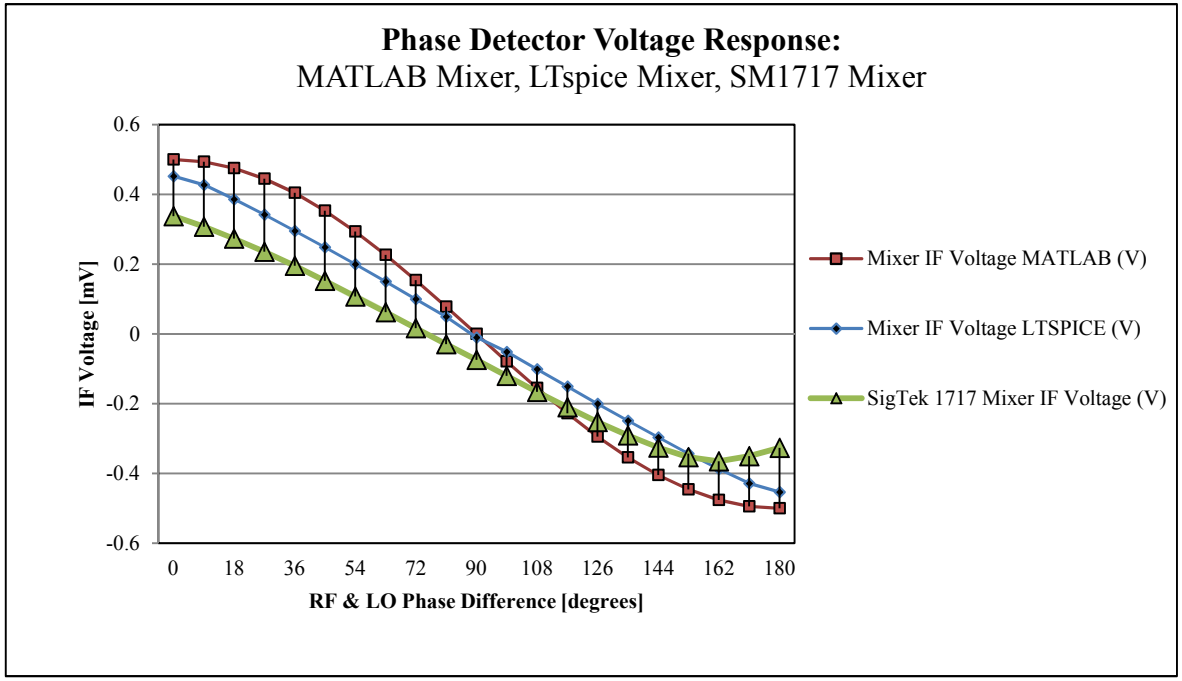
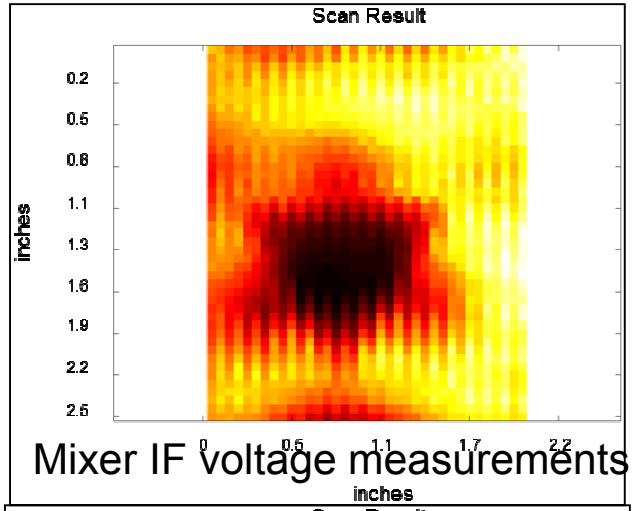
NFMM-PHASE Design Schematic

Phase Imaging Approach

- MATLAB vs. LTSpice vs. SM1717





Mixer IF voltage measurements

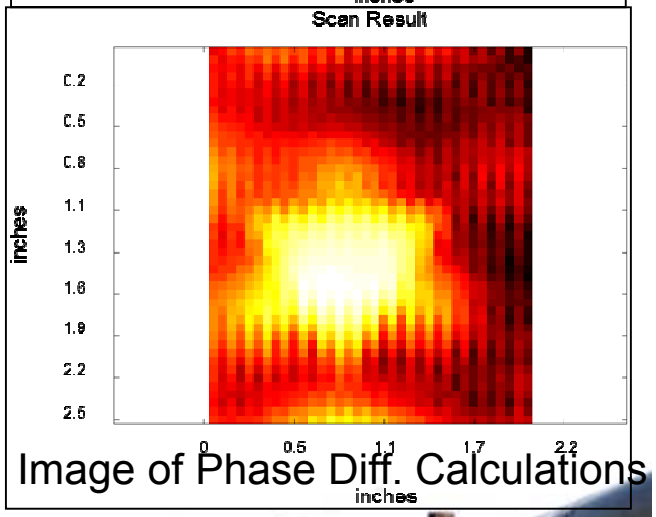
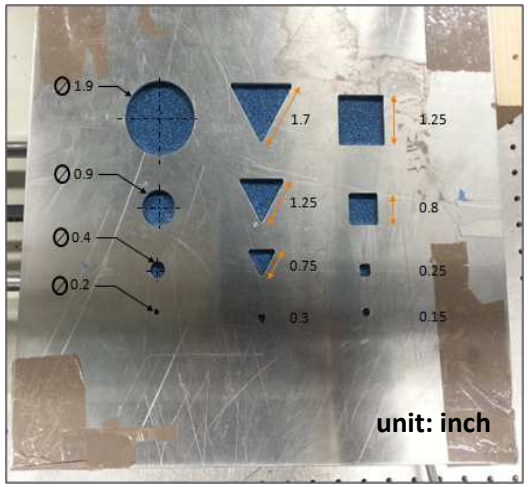


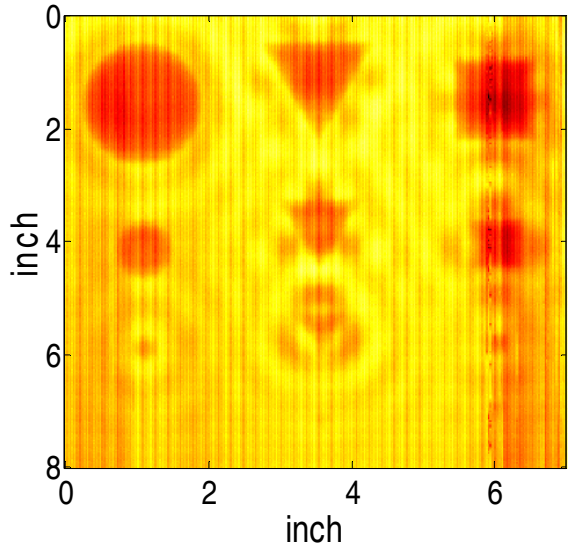
Image of Phase Diff. Calculations

Imaging Results: Calibration

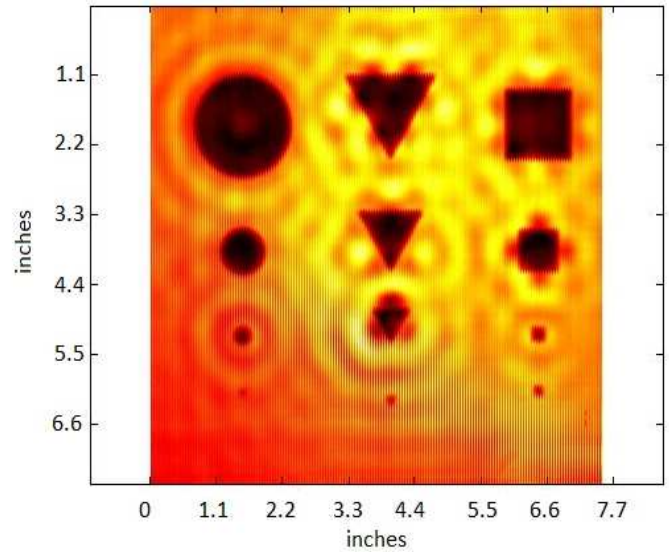
Calibration sample is used to test the system and image resolution before start scanning any target. Provide information for calculating the noise and artifacts in the system, such as **PSF** estimation.



Calibration Sample

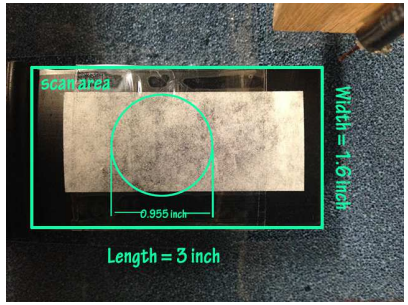


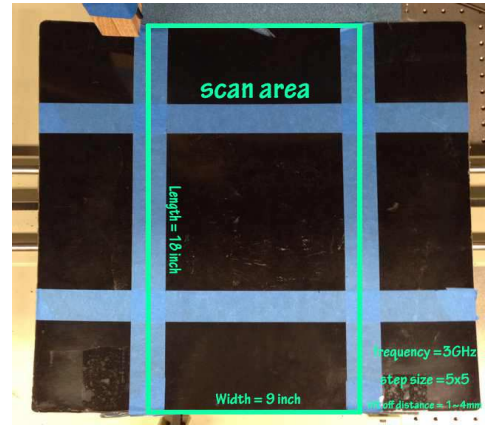
Amplitude Scan

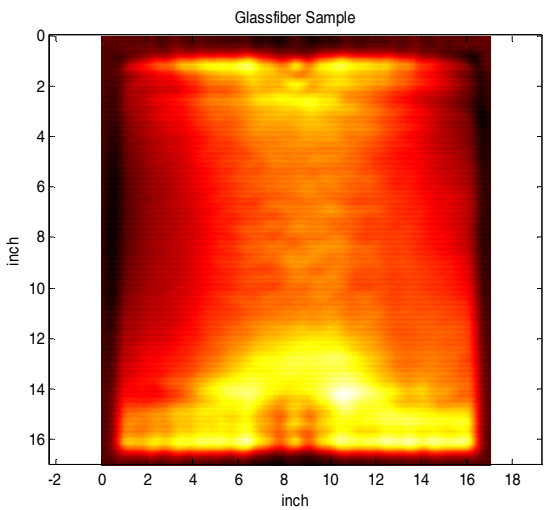


Phase Scan

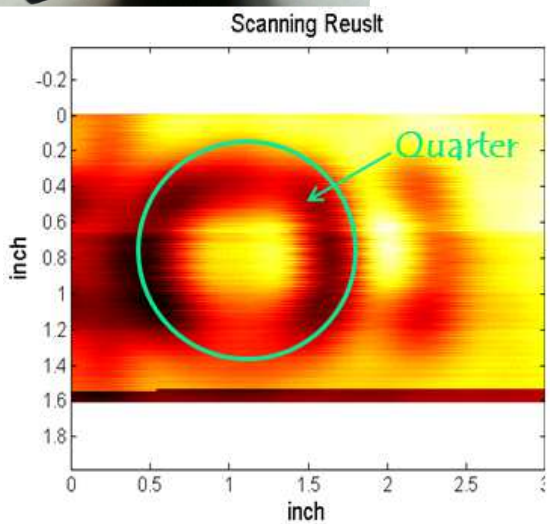
Amplitude Imaging



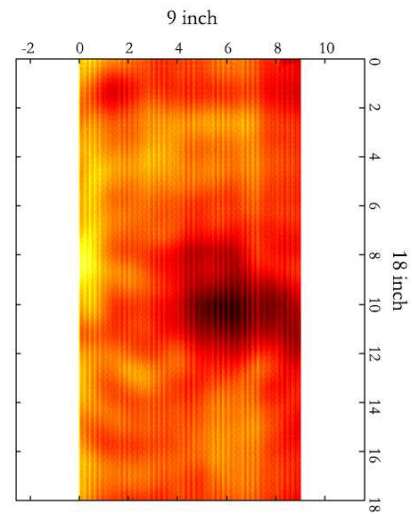




PA Sample

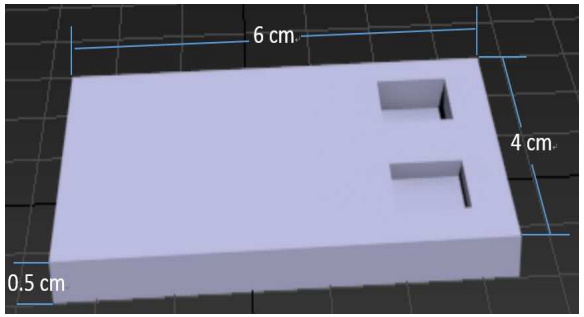


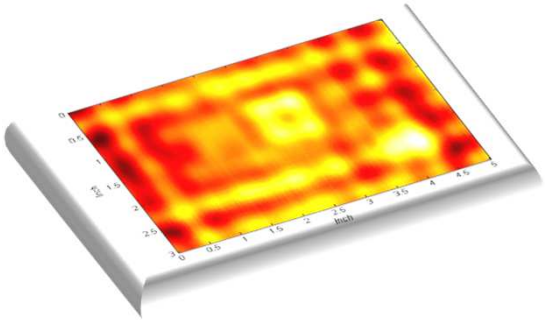
HDPE Sample



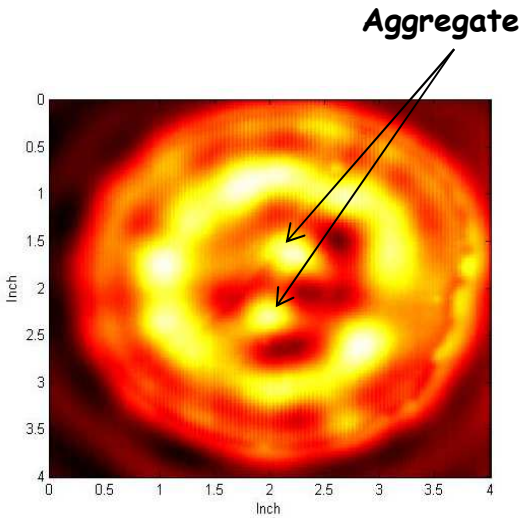
GFRP Sample

Phase Imaging: Broader Impacts

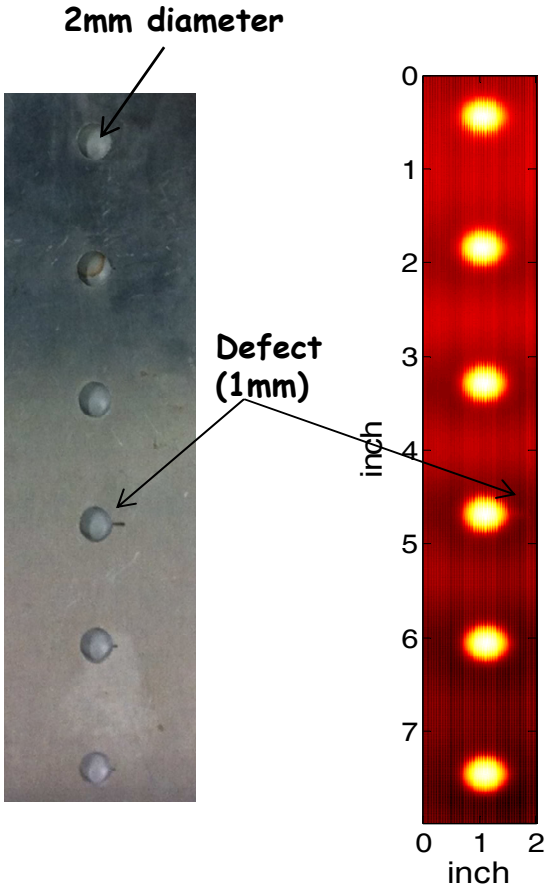




3D printed plastic sample



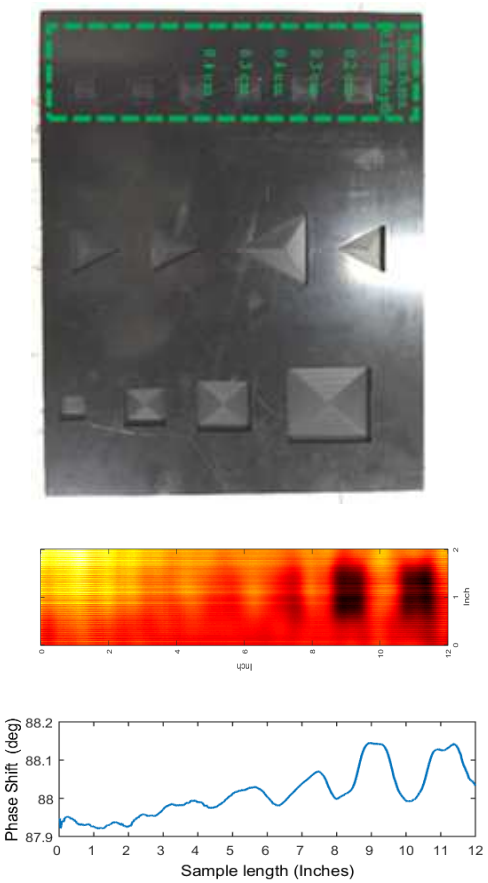
Concrete Sample before NaCl treatment



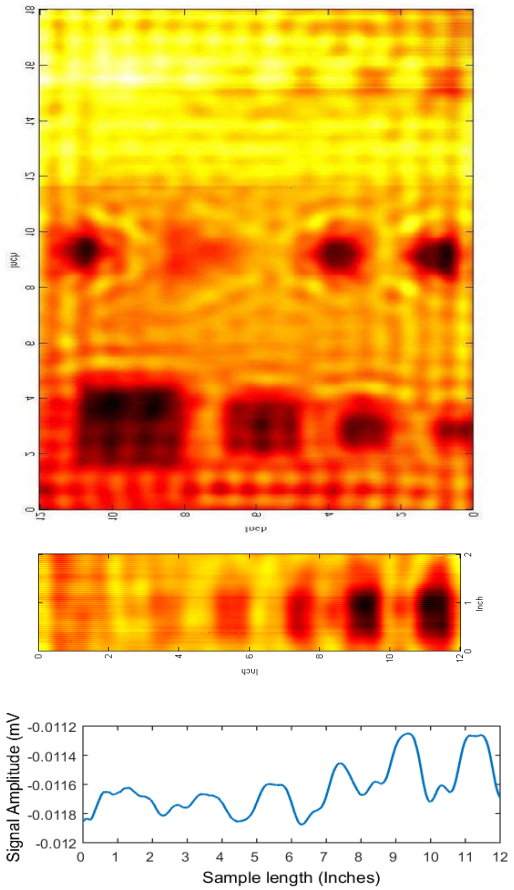
Multi-layer rivet hole sample with 1mm defect

PA-12 Sample

- Phase vs. Amplitude for PA-12 (Arkema)



Phase Measurement

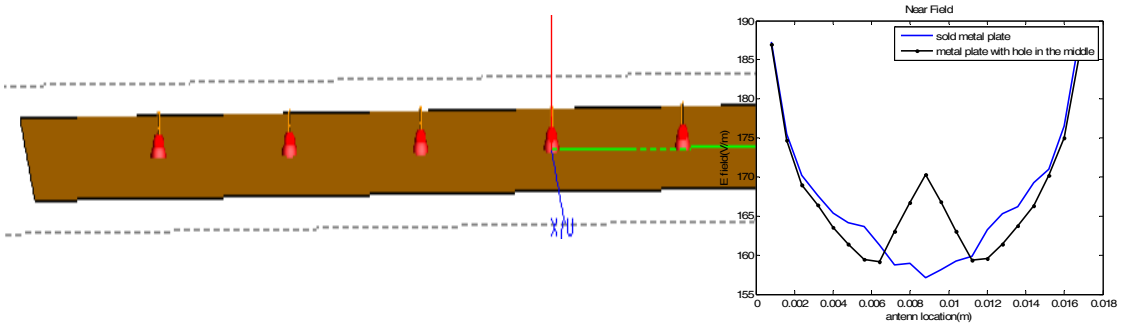


Amplitude Measurement

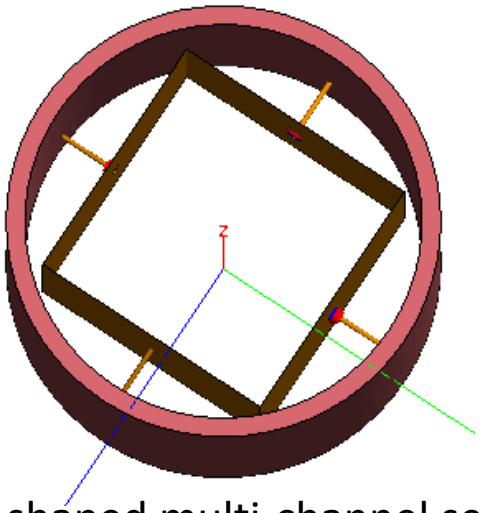
ILI Multi-channel NFMM Sensor Design

- A multi-channel NFMM sensor can improve the scanning speed and field of view by collecting data in multiple directions at the same time.
- Several simulation models have been developed to validate the design of multi-channel NFMM sensor.
  - Single hole-linear array model
  - Multi-size, multi-depth damage-linear array model
  - Circular array model (ongoing)

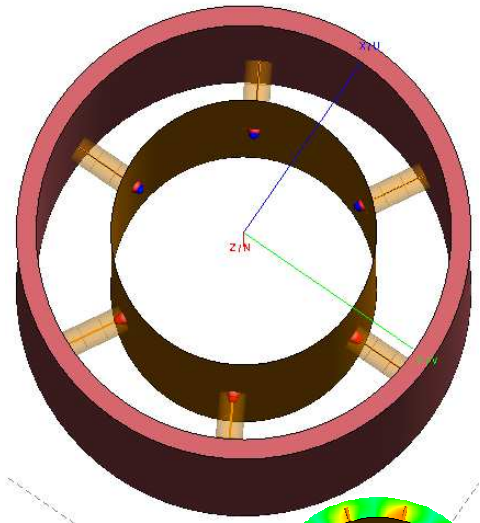
ILI Multi-channel Sensor Design

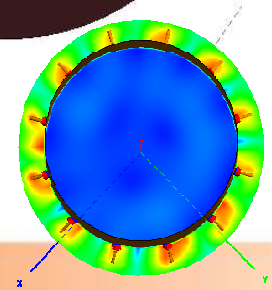


(a) Multi-channel sensor on a metal plate. Only collect data from one direction. Better ground plane. Easiest design. Not suitable for pipe injurious detection.



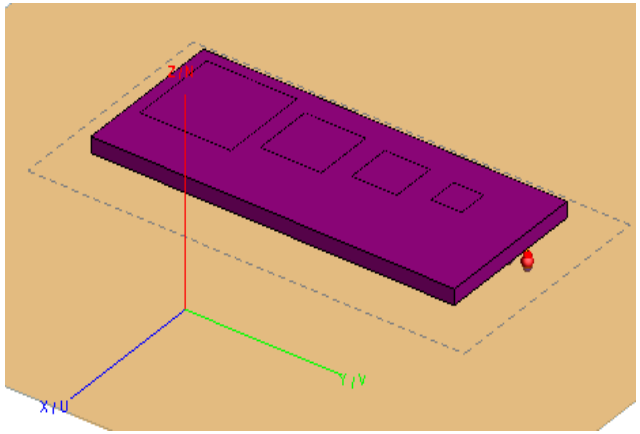
(b) Cubic shaped multi-channel sensor. Able to collect data from four directions. Limited number and size for scanning probes.

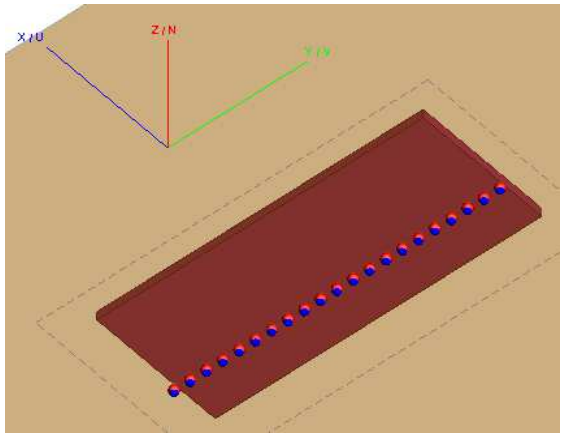




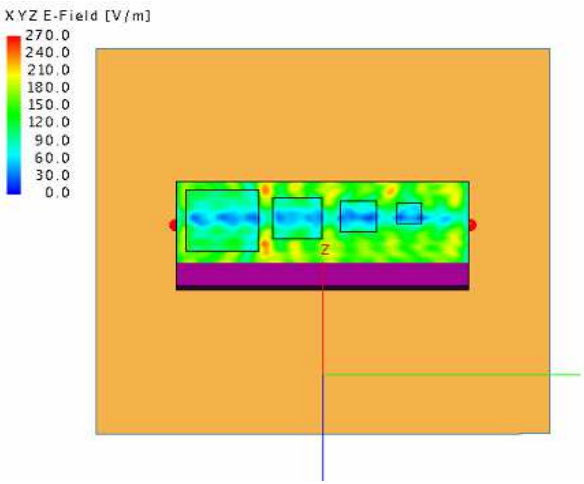
(c) Pipe shaped multi-channel sensor. Able to collect data from all different directions. No limit for either number or size of the scanning probes. Ground plane is not perfect due to the shape of the scanner.

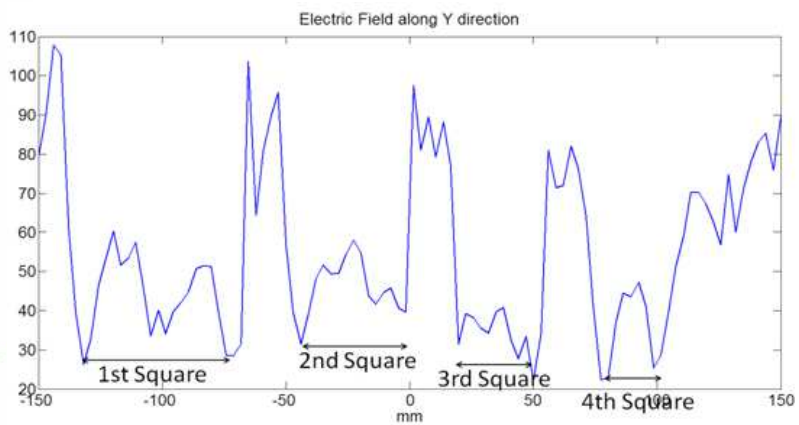
Simulation Results: 3-D



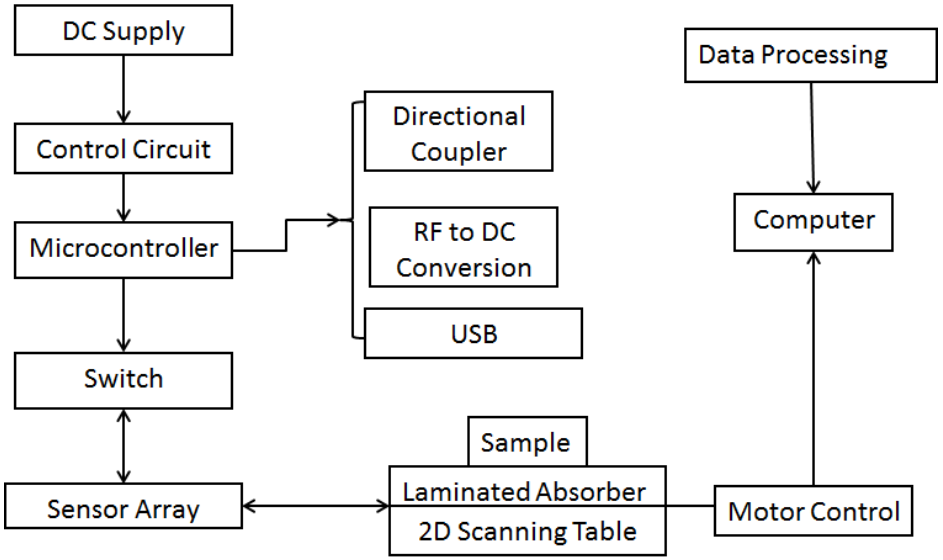


Simulation geometry:
Sides of each square:
76.2mm, 50.8mm, 38.1mm, 25.4mm
Plate size:
457mm x 305mm x 10mm





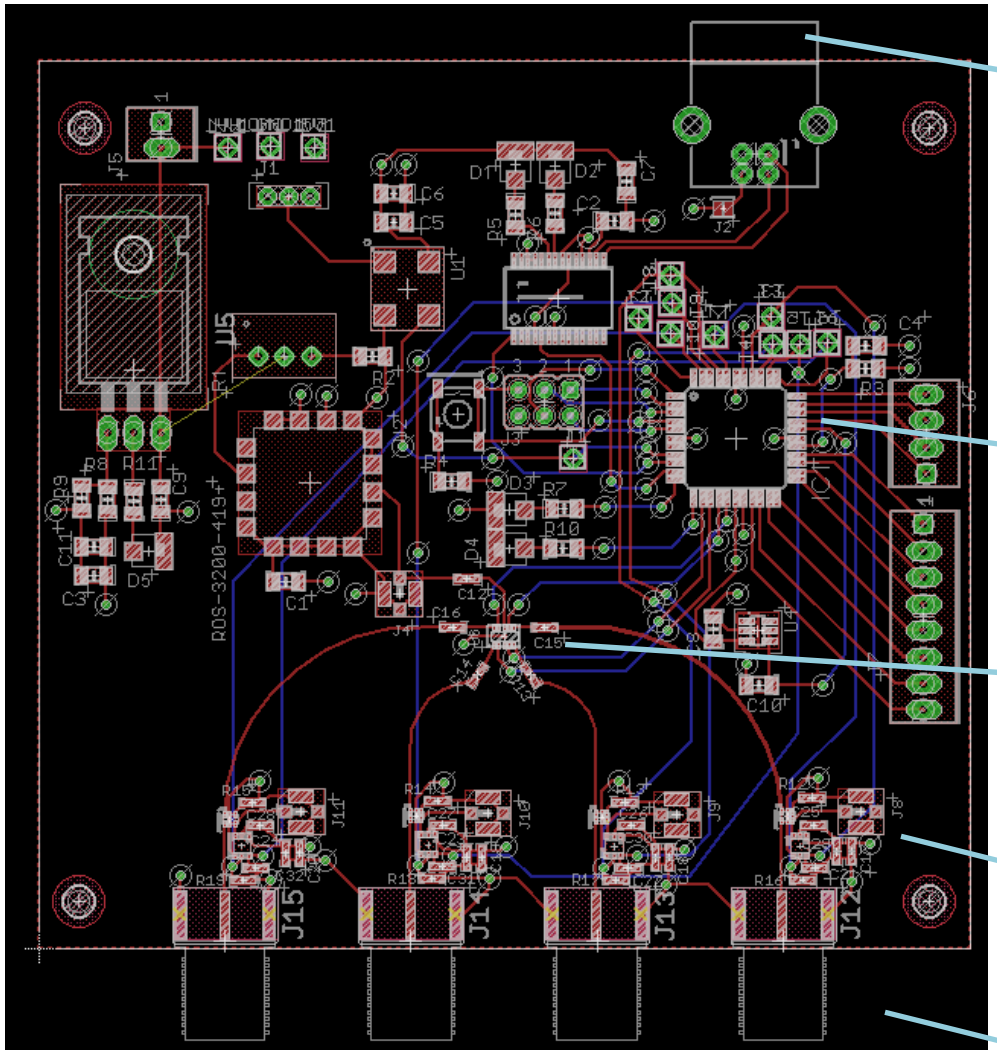
Multi-channel Sensor Prototyping



NFMM System Schematic with Multi-channel array

1. Micro Controller: sequentially sending/receiving signal to/from each antenna. The micro controller we choose now has the ability to extend the array to 8 elements
2. USB receiving data: store date for later processing, saving scan time
3. RF to DC converter
4. Voltage Oscillator: control input frequency, able to change frequency for different size antenna

Multi-channel Sensor Prototyping



USB Reader

Control Unit

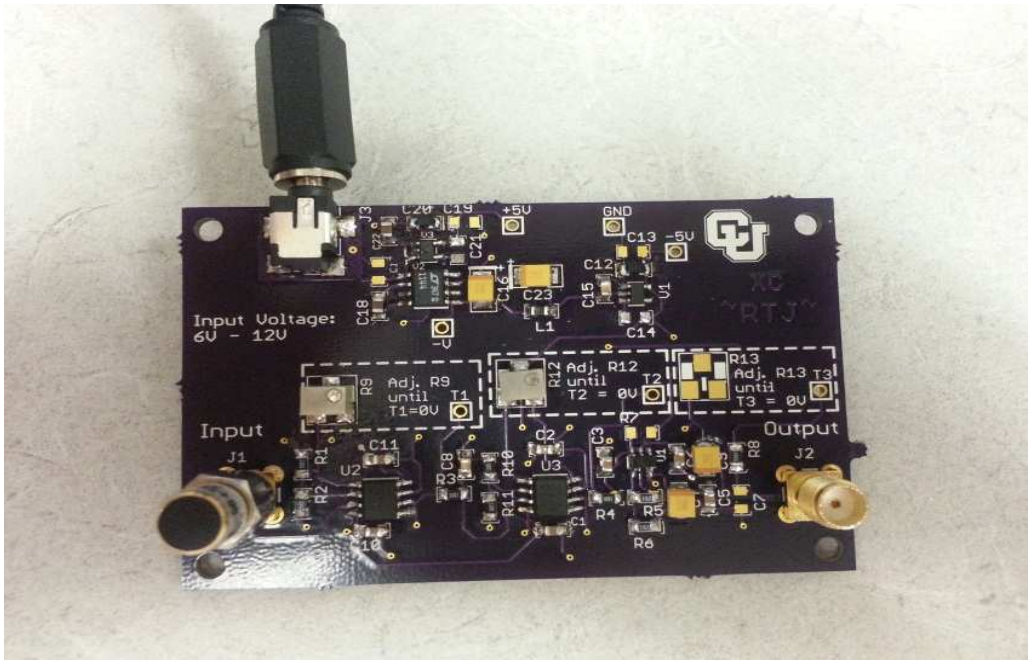
Switch for choosing array element

Directional Coupler and RF to AC conversion

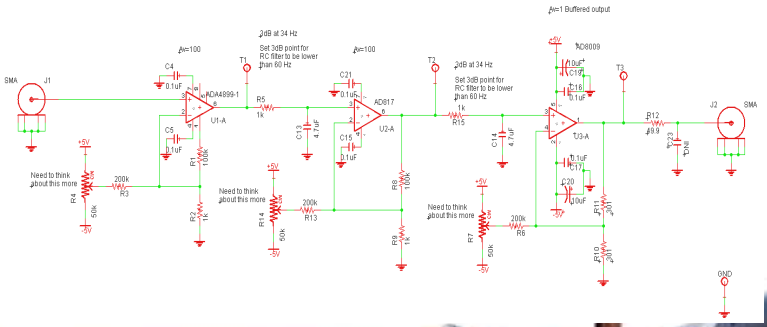
Antenna Array

DC signal amplifier circuit design

Since the return signal in our system is at milli-volts range, to improve the quality of the image, a stronger return signal is required. The amplifier circuit was designed to have the ability to amplify the signal up to 10000 times. Each stage also has an adjustable resistor to increase the signal-to-noise ratio.



completed printed circuit board and mounted components made by the CU CAAP research group



Issues of Current Single Sensor Imaging: Speed

- The initial scanning time for area (190 mm x 100 mm) with step size 0.635 mm is **long**.
  - 48,000 spatial locations are covered.
  - Each spatial value is average of 3000 samples.
  - Resulting 144 million samples are acquired and processed.
- High data storage capacity, more computation power.
- Data size problem could be solved by using <u>various compression techniques (e.g. **transform coding**)</u> with inherent inefficiencies.

Proposed Solution

- **Directly acquire a compressed signal at sensing level**
- **Observations:** Near field microwave signals shows sparsity in DCT and/or image domain.
- Consequently, Compressive Sensing(CS) method is proposed for NFMM to significantly reduce the number of spatial samples required for 2-D/3-D imaging and data reconstruction.
  - Raster Scanner can skip random spatial locations in x-y plane.
  - Resulting less data acquisition time as well as less computation requirement.
- Original signal is then reconstructed by using Basis Pursuit and Matching Pursuit algorithms (refer to **Appendix**).

Optimization in NFMM setup

- Raster scanning path is altered according to the percentage of data collection.
- Skipped spatial points are same in every column. (number of skipped rows become the number of skipped spatial points in a column).
- Resulting total scan time is significantly reduced significantly with smaller data size.
- Computational effort required is light because number of samples acquired are lesser.
- Proof-of-Concept 1-D results in **Appendix**

2-D Results

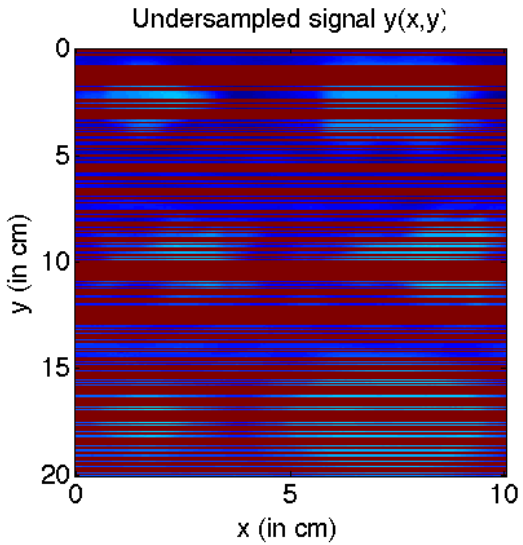


Fig. 15

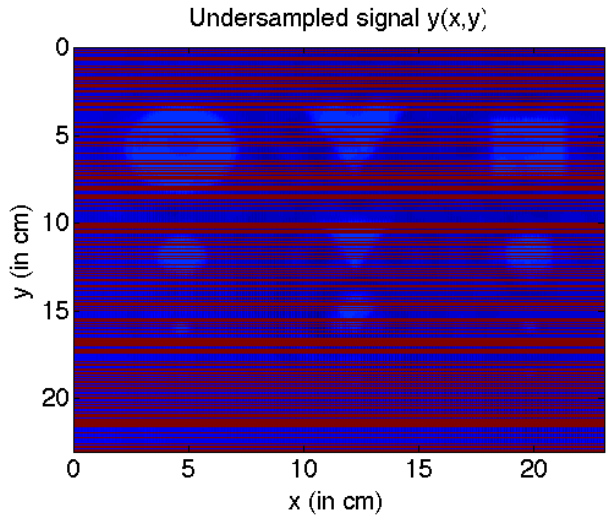


Fig. 16

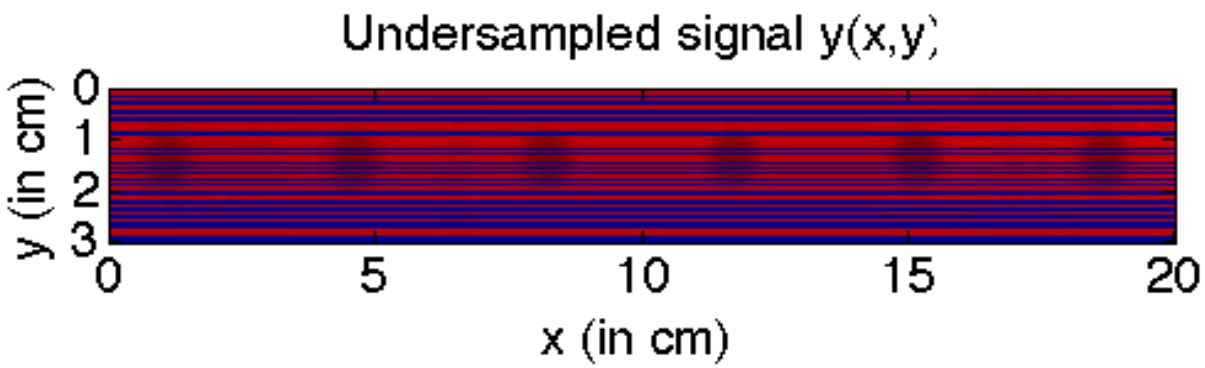


Fig. 17

2-D Results

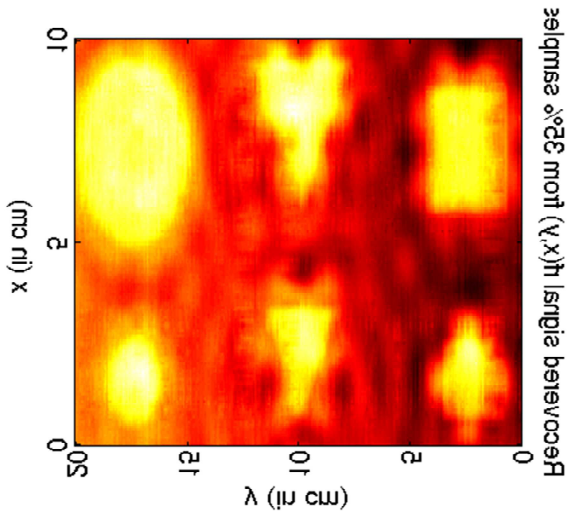


Fig. 18

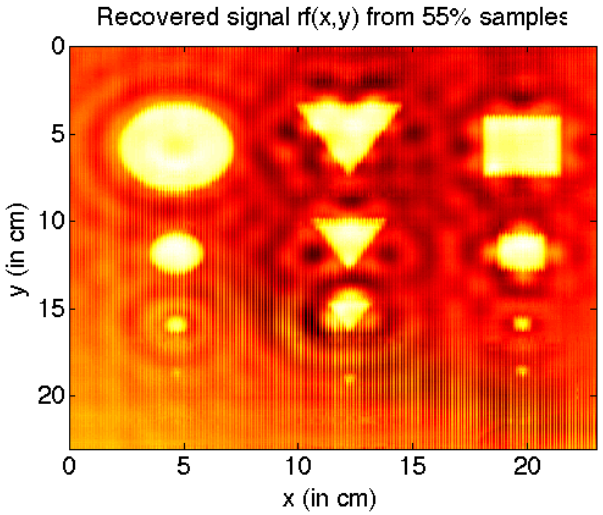


Fig. 19

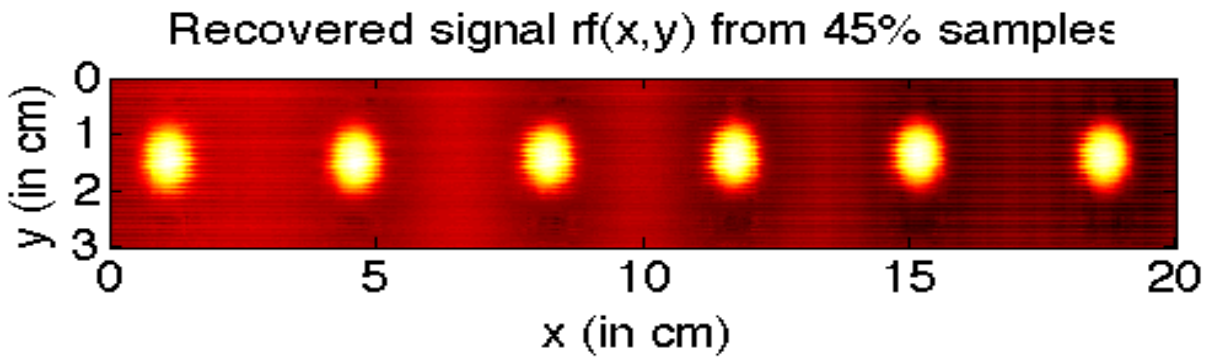
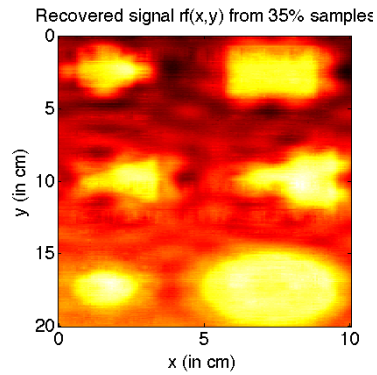
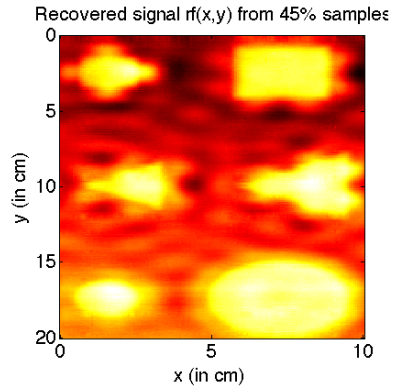


Fig. 20

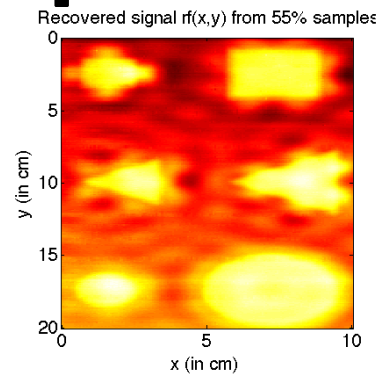
Additional Experiments



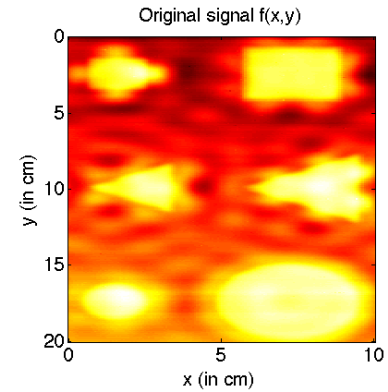
PSNR= 70.29
Time= 18.61s



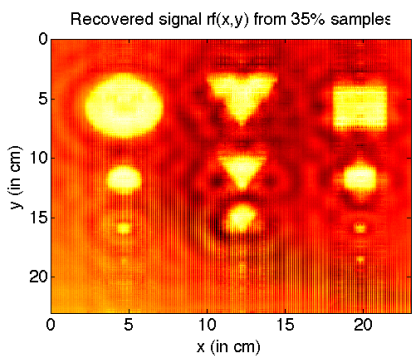
PSNR= 73.13
Time= 13.46s



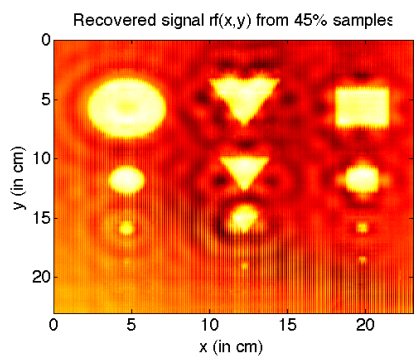
PSNR= 79.69
Time= 33.06s



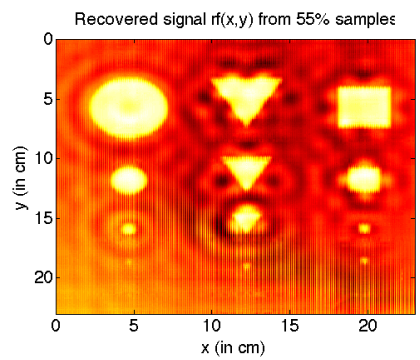
Original Signal



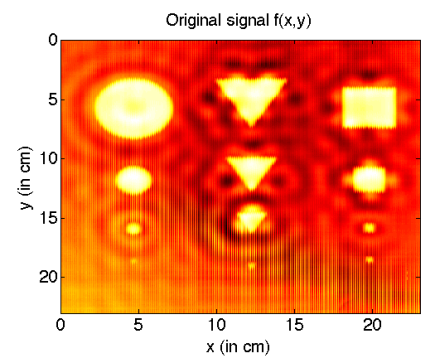
PSNR= 63.66
Time= 33.59s



PSNR= 70.10
Time= 37.15s

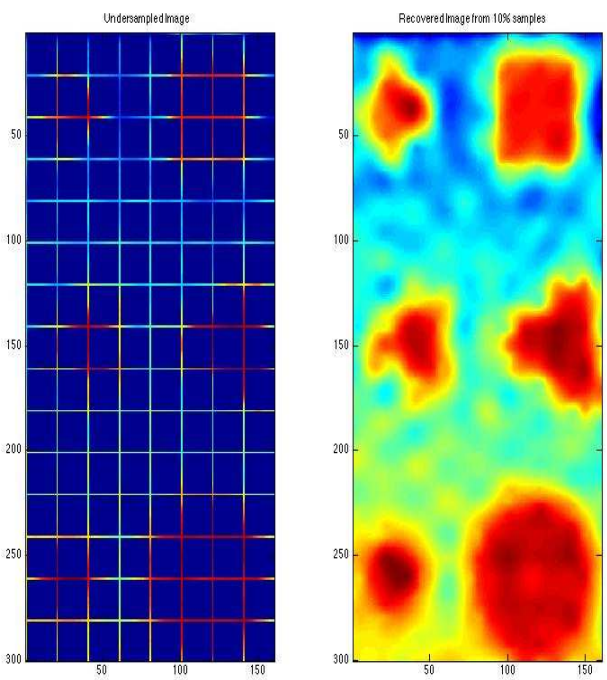


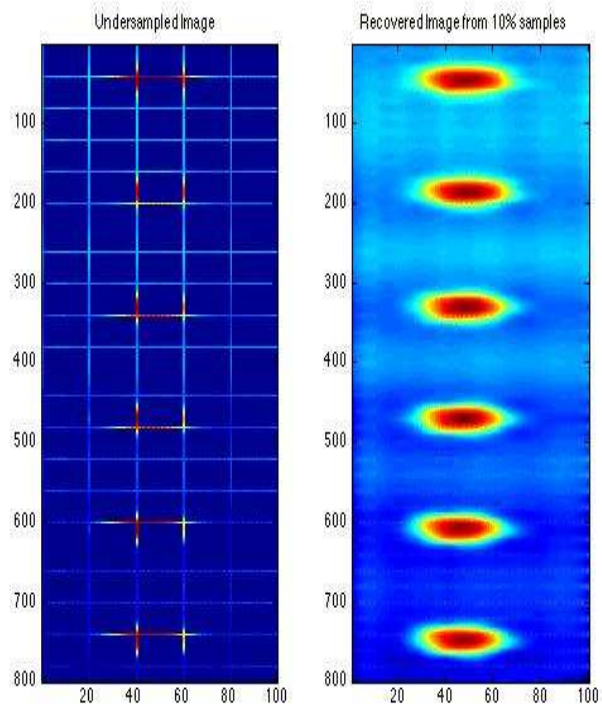
PSNR= 71.98
Time= 41.92s



Original Signal

Faster: 2-D Grid Sampling

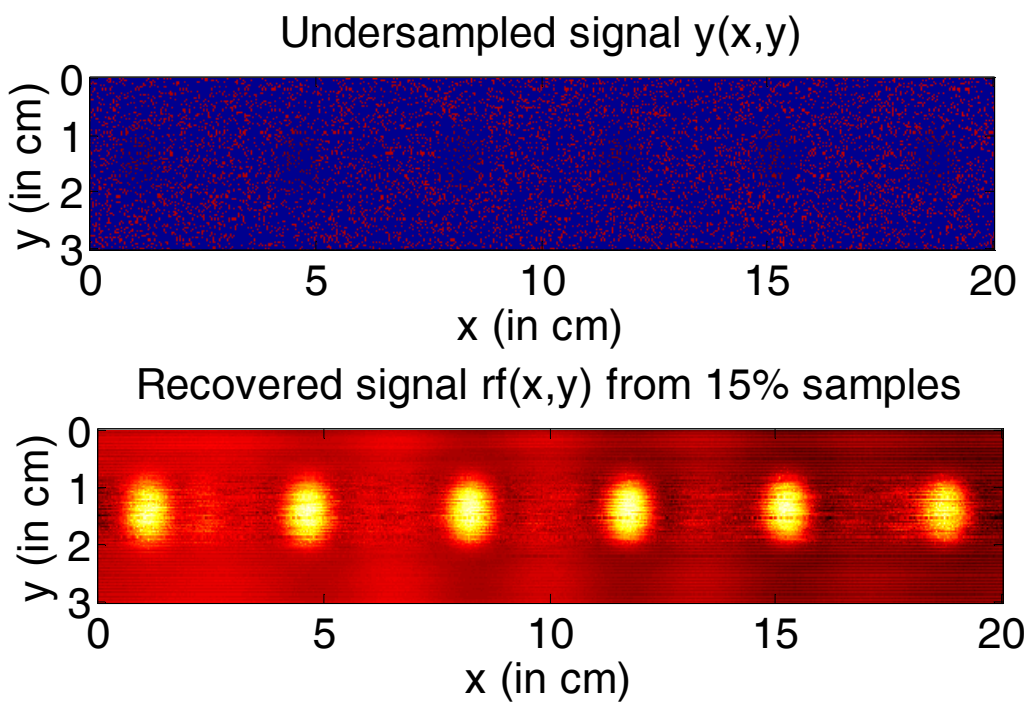




Information in K-sparse compressible signal not damaged by the dimensionality reduction

2-D Random and Continuous sampling

- Continuous Sampling with 15% data



Future Directions

- Fabricate and test the sensor array on ILI platform. Increase the number array elements in both linear and circular settings (more complicated than what we originally expected)
- Fast Imaging and Data acquisition. Efficient 3D defect reconstruction and imaging using onboard high performance computing (NDE to SHM?)
- Improve NFMM probe/tip design for more superior resolution and sensitivity (More applications)
- Fast Imaging for ILI platform with better 3D data reconstruction

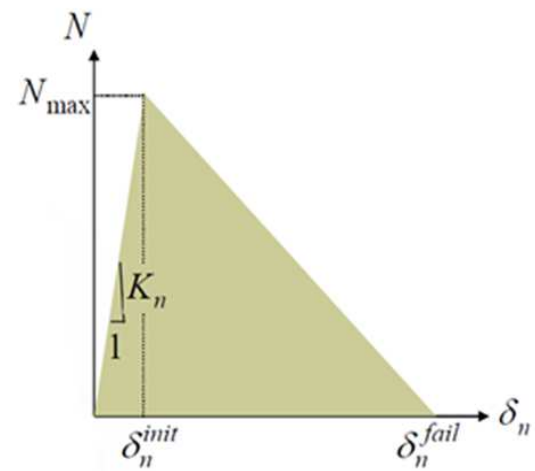
Accomplishments - ASU

- Develop a general simulation framework using extended finite element method (XFEM) + cohesive zone modeling (CZM) for impingement failure prediction
- Design of experiments (DOE) and response surface method (RSM) methodology for prognosis model development
- Develop a general information fusion framework by integrating the numerical simulation and diagnosis results (CU DENVER) based on Bayesian updating technique

XFEM+CZM framework for simulation

- Classical finite element method (FEM) with adaptive meshing can be used , but it is very time consuming for propagating crack in large system analysis.
- XFEM uses enrichment function to avoid meshing the crack geometry

Traction-separation law

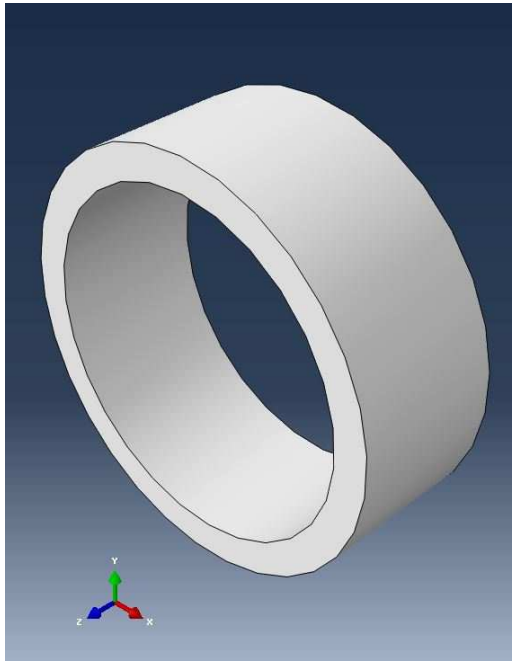


N_{max}= peak stress
δ_n^{fail} = strain at failure

- XFEM+CZM can simulate the crack initiation and propagation without prior knowledge of the crack path

Model development and simulation under static loading

- Pipe geometry with impingement-induced surface cavity



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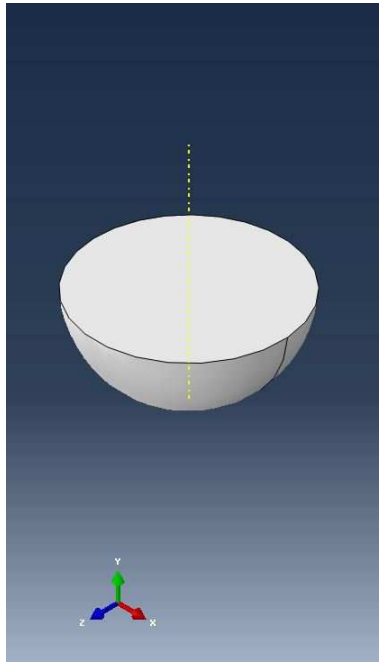

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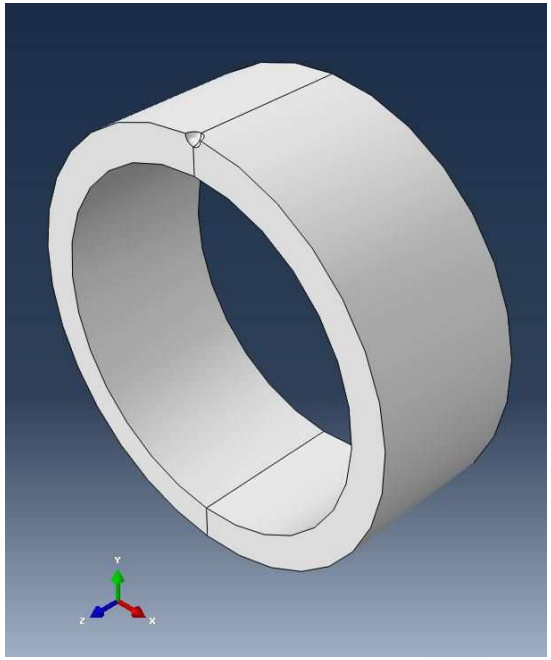
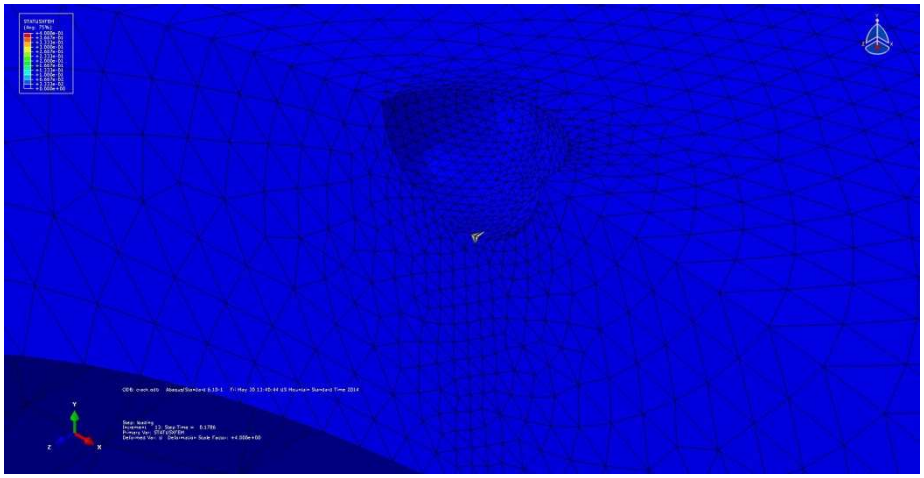
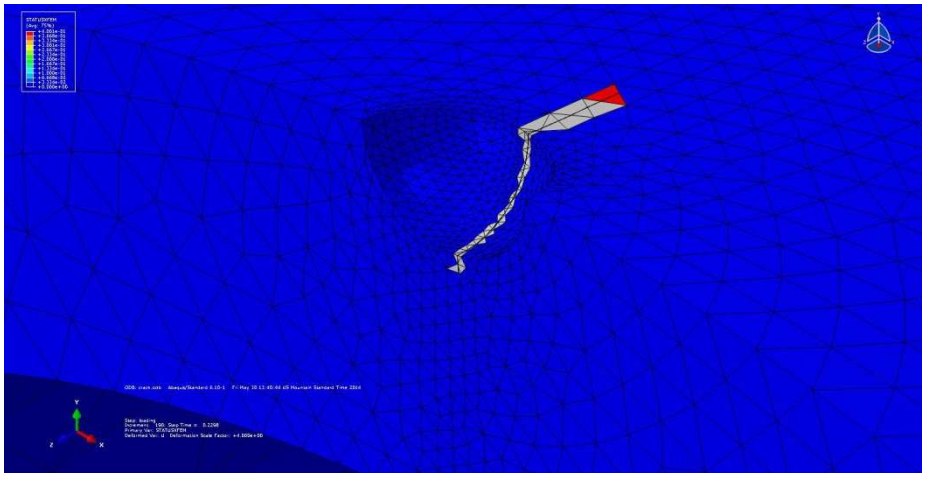
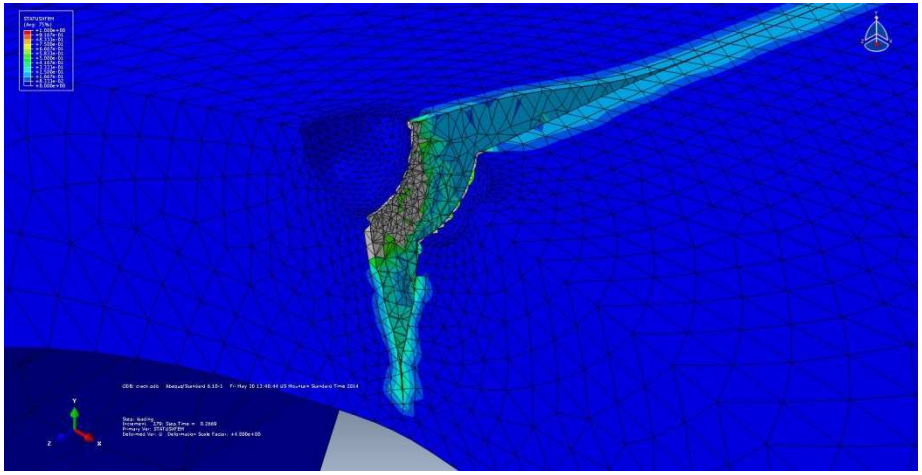
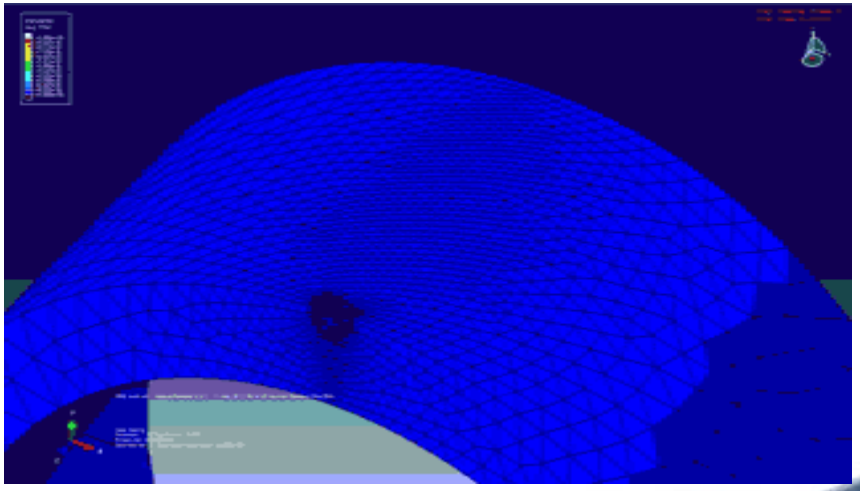


SIMULATION – CRACK GROWTH









Slow crack growth analysis – impingement and creep

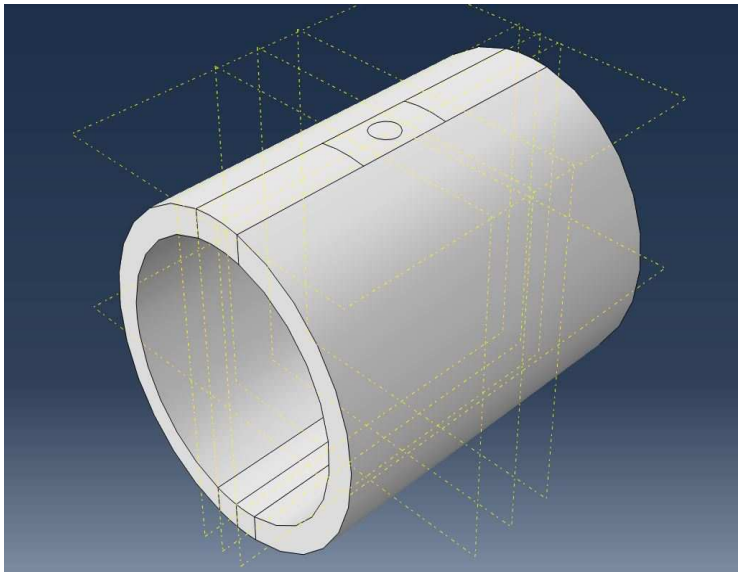
- Large impingement loading under long term duration causes the accumulated creep deformation and slow crack growth in pipes
- A simple power creep law is used

$$\acute{\varepsilon} = A\,\sigma^n\,t^m$$

where

$\acute{\varepsilon}$ is the uniaxial equivalent creep strain rate,
σ is the uniaxial equivalent stress,
t is the total time, and
A Power law multiplier
n Equivalent stress order
m Equivalent time order

Slow crack growth analysis – model parameters

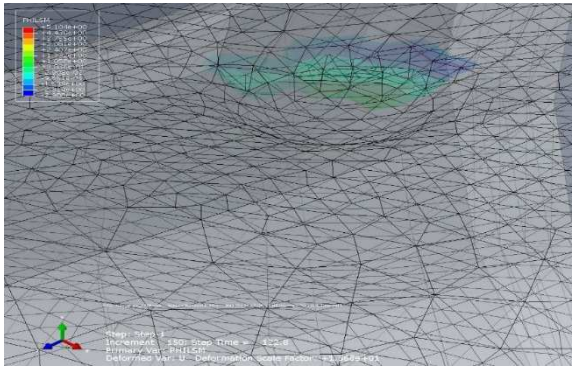


S. No.	PROPERTY	TYPICAL VALUE	UNIT
1	Power law multiplier	2.145e-3[b]	MPa^{-n} $time^{-1}$
2	n	6.5	NA
3	m	0.0	NA
4	Peak stress	51[a]	Mpa
5	Fracture Energy	620[a]	KJ/mm^2

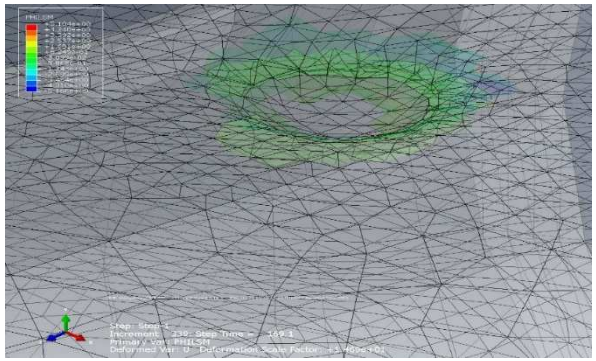
[a] Lucien Laiarinandrasana, Guillaume Boisot, C. Fond, Gilles Hochstetter. Toughness improvement of polyamide 11 assessed via quasistatic tensile tests on notched round bars. ed. D. Klingbeil, M. Vormwald, K.G. Eulitz. Fracture of materials and structures from micro to macro scale - ECF 18, Aug 2010, Dresden, Germany. DVM, 8 p.

[b] G. Boisot, L. Laiarinandrasana, , , J. Besson, C. Fond, G. Hochstetter "Experimental investigations and modeling of volume change induced by void growth in polyamide 11" International Journal of Solids and Structures, Volume 48, Issue 19, 15 September 2011, Pages 2642–2654

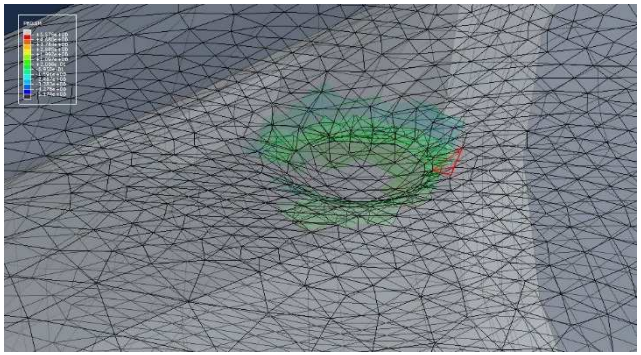
Slow crack growth analysis – formation of indentation



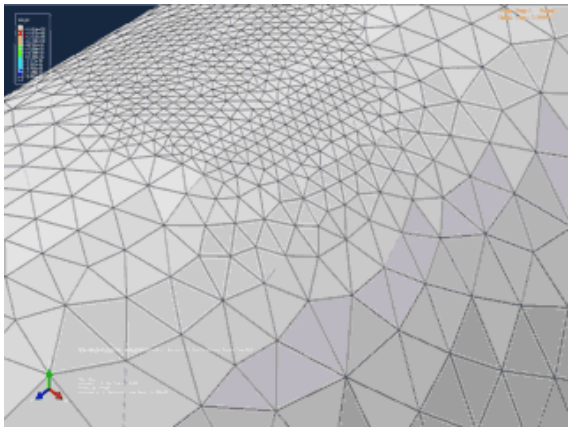
Indentation formation at time period 122



Indentation formation at time period 140



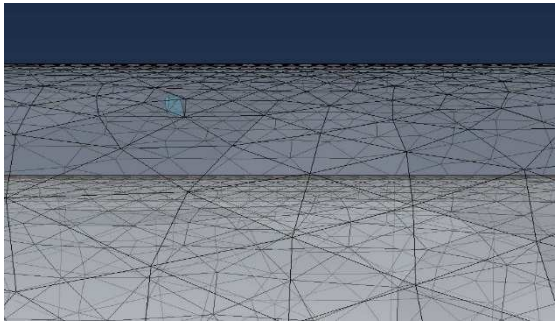
Indentation formation at time period 240



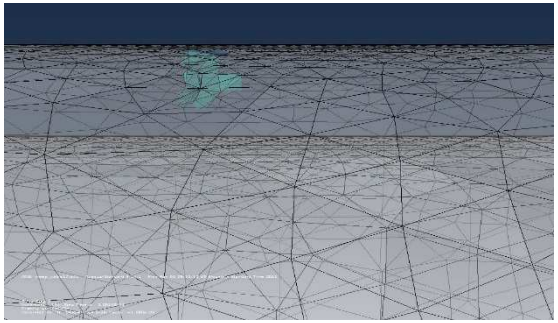
Simulated forming process

Field observation

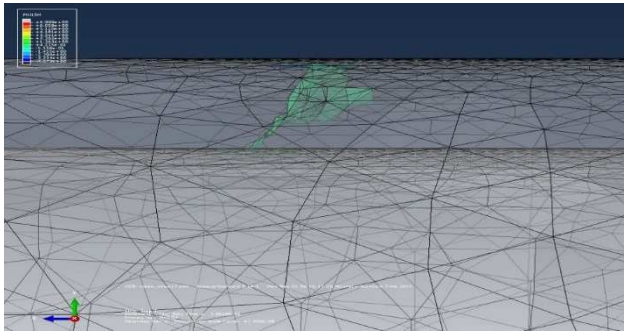
Slow crack growth analysis – crack propagation



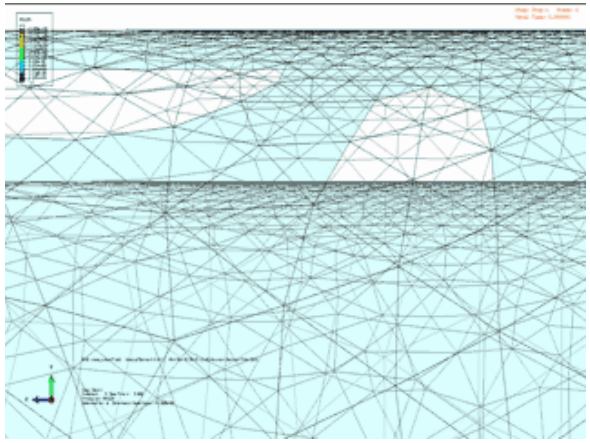
Crack propagation at time period 40



Crack propagation at time period 120



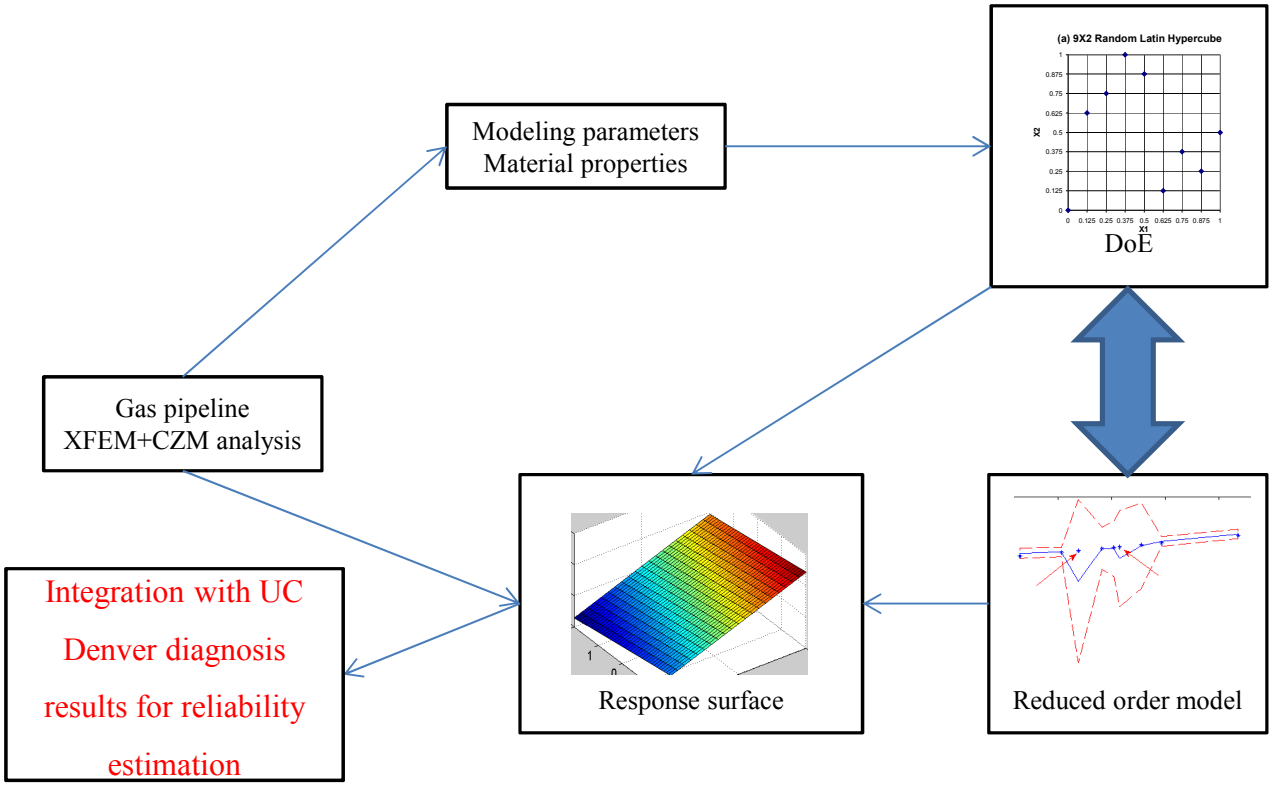
Crack propagation at time period 240



Simulated crack propagation process

Field observation

Probabilistic prognosis framework



Design of experiment (DoE)

In engineering, DoE is used to investigate the effect of parameters of interest on the system response

- Full factorial design

  The number of samples for parameters, with dimeision D and three designs for each dimension

$$\text{Number of samples} = 3^D$$

  Intractable for higher dimensional problems

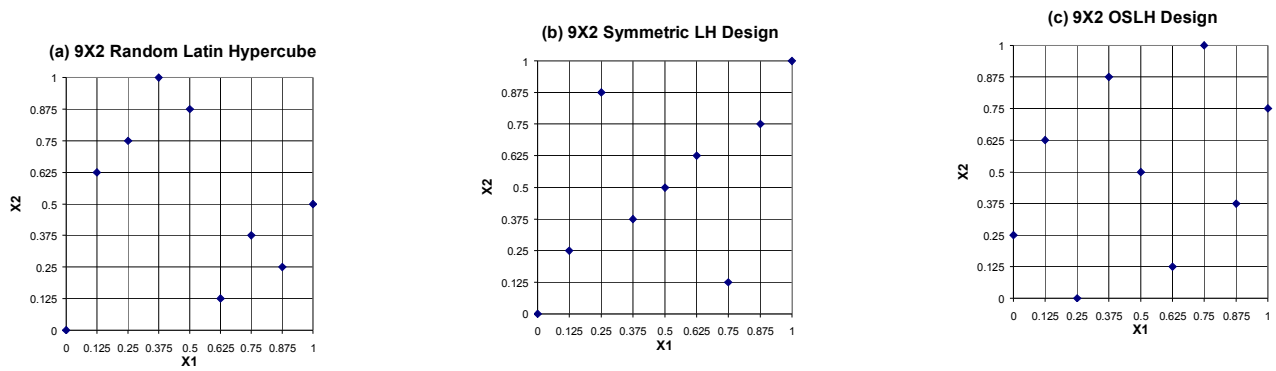
- Latin Hypercube design

  Generate arbitrary number of samples and the number of samples is independent of dimensions

  Each dimension can be represented equally

Latin hypercube design

- A Latin hypercube is a set of n points in D dimensions with the property that the projections on any axis form a uniform n-grid
- Random LHD, Symmetric LHD, Orthogonal LHD



- LHD based on criteria, such as entropy, mean-square error, or maximize the minimum distance between points

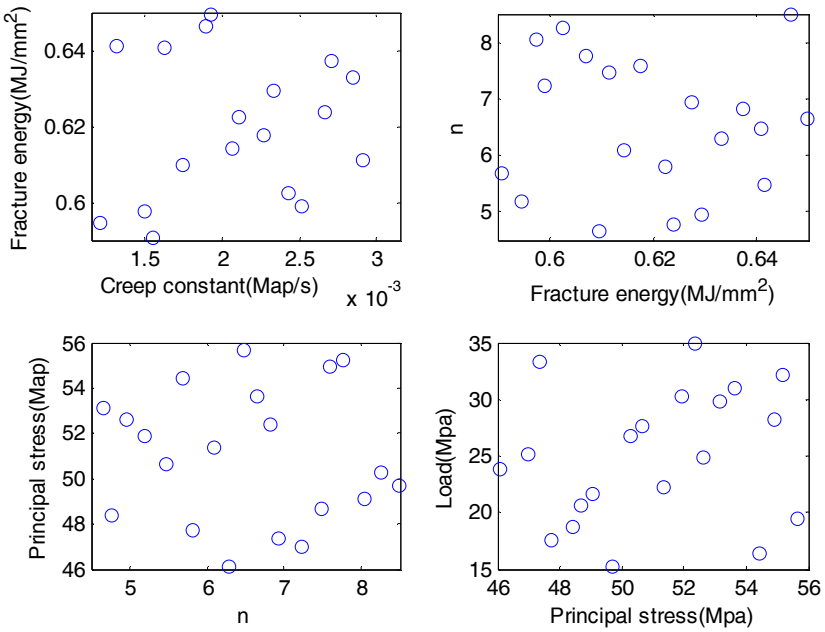
Response surface modeling -Design parameters

- For demonstration, five random variables are chosen for DOE
- The sampling interval for each parameter $[\mu - \Delta, \mu + \Delta]$

Random variable	Creep constant (MPa/s)	Fracture Energy (MJ/mm^2)	n	Principal stress (MPa)	Load (MPa)
Mean	2.15×10^{-3}	0.620	6.5	51	25
Sampling interval	$[1.15,3.25]\times 10^{-3}$	[0.590, 0.650]	[4.5,8.5]	[46,56]	[15,35]

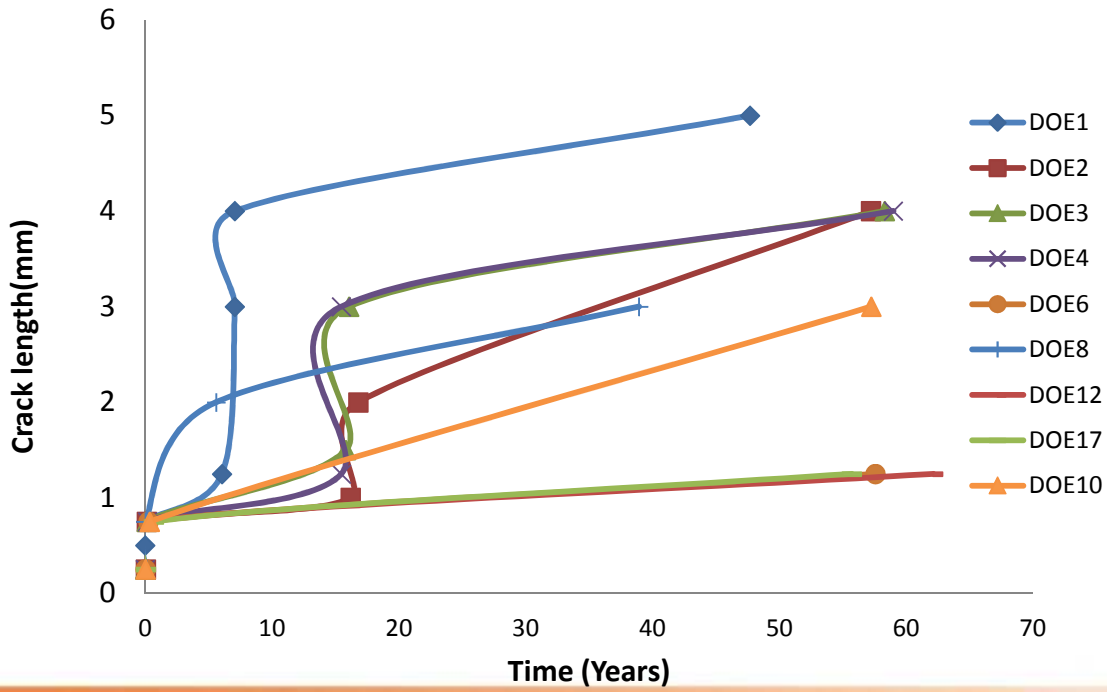
Initial design and 2-D projection

- Initial 20 DoEs are generated using Latin Hypercube sampling
- The projection of those 20 samples on each 2-D plane are shown below



Simulation results

- Highly nonlinear crack propagation behavior
- Huge variation with different loadings and material properties



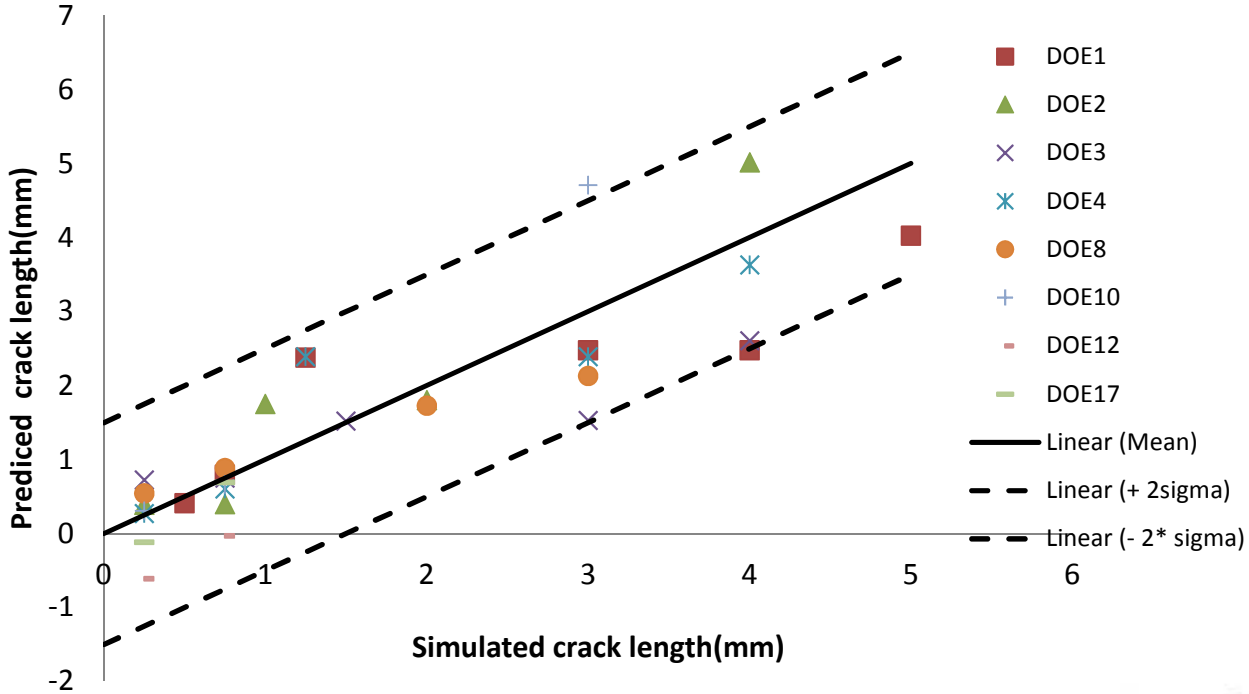
Regression model

$$Crack\ length = g(x, P) = f_1(P)x^{f_2(P)} + f_2(P)$$

where $f_1(P)$=$\alpha_0 + \alpha_i p_i$, $f_2(P)$=$\beta_0 + \beta_i p_i$, $f_3(P)$=$\gamma_0 + \gamma_i p_i$

p_i represents 5 design variables

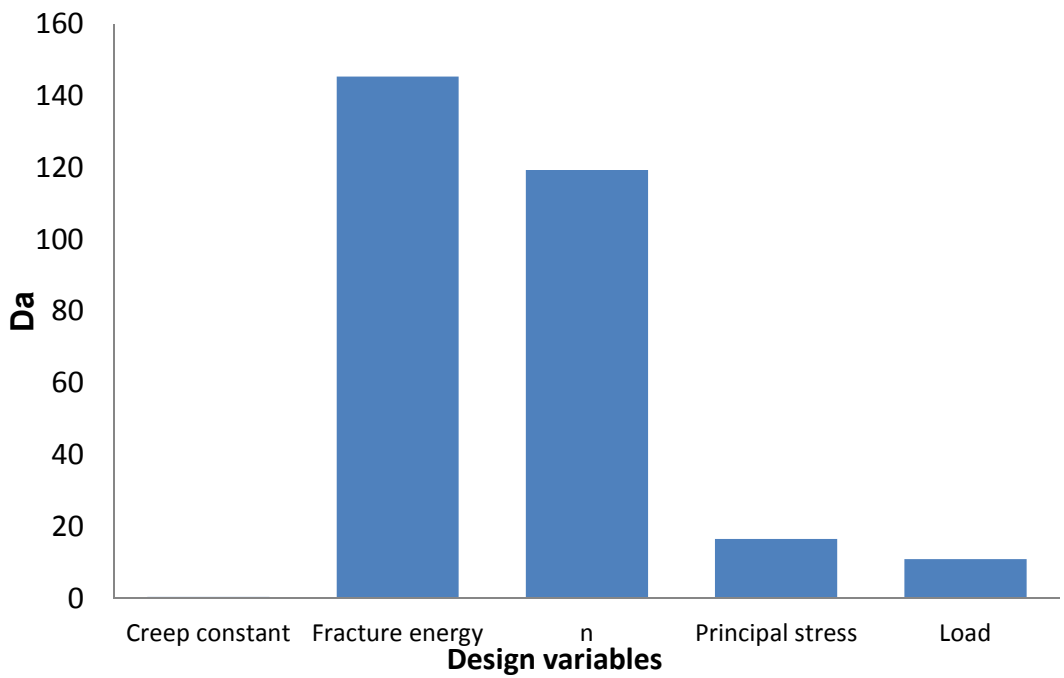
x is the creep time



Sensitivity analysis

Investigate the crack length difference Δa with respect to variation of each design variable at creep time $x = 10$ years

$$\Delta a = \left| g\left(x, \mu_{pi}\right) - g\left(x, \mu_{pi} + 0.1\mu_{pi}\right) \right|$$



Probabilistic analysis

- The response surface model is obtained by fitting the data and the effect of design variables is included in the model explicitly
- With the help of this response surface model, complex finite element analysis can be avoided when doing probabilistic analysis using the Monte Carlo method
- All the design variables are considered as random variables in the probabilistic analysis

Random variable	Creep constant (MPa/s)	Fracture Energy (MJ/mm^2)	n	Peak stress (MPa)	Load (MPa)
PDF	Normal	Normal	Normal	Normal	Normal
μ	2.15	0.62	6.5	51	25
σ	0.5	0.015	1	2.5	5

Bayesian inference

- Assume $\theta = [p_1, p_2, p_3, p_4, p_5]$, the posterior distribution of θ is given as

$$\boldsymbol{q}(\boldsymbol{\theta}) \propto \boldsymbol{p}(\boldsymbol{\theta})\boldsymbol{p}(\boldsymbol{x}'|\boldsymbol{\theta})$$

where $\mathrm{p}(\mathrm{x}'|\theta)$ is the likelihood function, $p(\theta)$ is the prior belief of the parameters, x' is the synthetic measurements. In our formulation, the relationship between x' and $\mathrm{M}(\theta)$ is expressed as

$$\boldsymbol{x}' = \boldsymbol{M}(\boldsymbol{\theta}) + \boldsymbol{e}$$

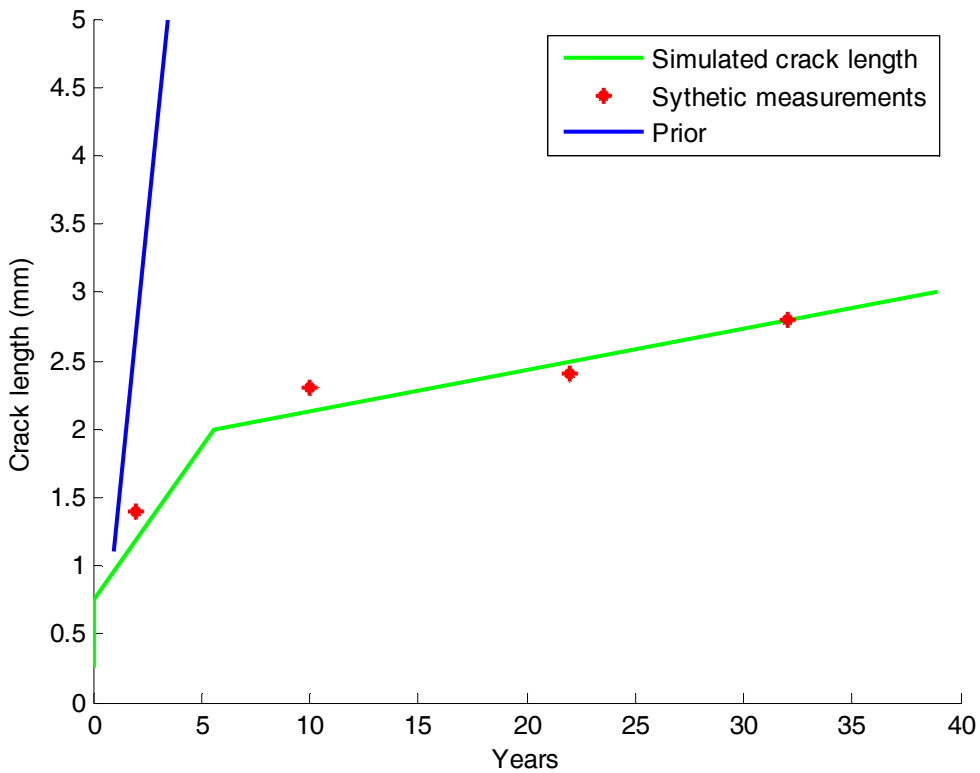
where $\boldsymbol{e}$ is the error between synthetic measurements and simulated creep crack length. Thus, the likelihood function $\mathrm{p}(\mathrm{x}'|\theta)$ can be expressed as

$$p(x_1', x_2', \dots x_n'|\theta) = \frac{1}{\left(\sqrt{2\pi}\sigma_e\right)^n} exp\left(-\frac{1}{2}\sum_{i=1}^{n}\left(\frac{(x_i' - M(\theta))}{\sigma_e}\right)^2\right)$$

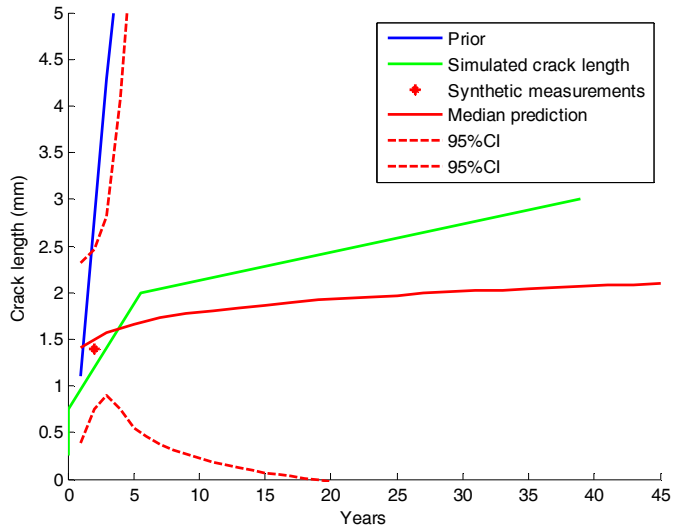
- The posterior distribution of parameter θ can be expressed as

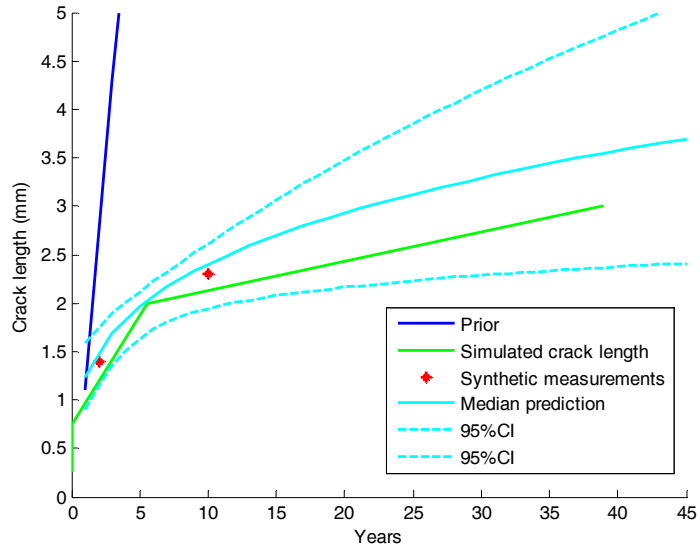
$$p(\theta|x_1', x_2', \dots x_n') \propto p(\theta)\frac{1}{\left(\sqrt{2\pi}\sigma_e\right)^n} exp\left(-\frac{1}{2}\sum_{i=1}^{n}\left(\frac{(x_i' - M(\theta))}{\sigma_e}\right)^2\right)$$

Prior belief and synthetic data

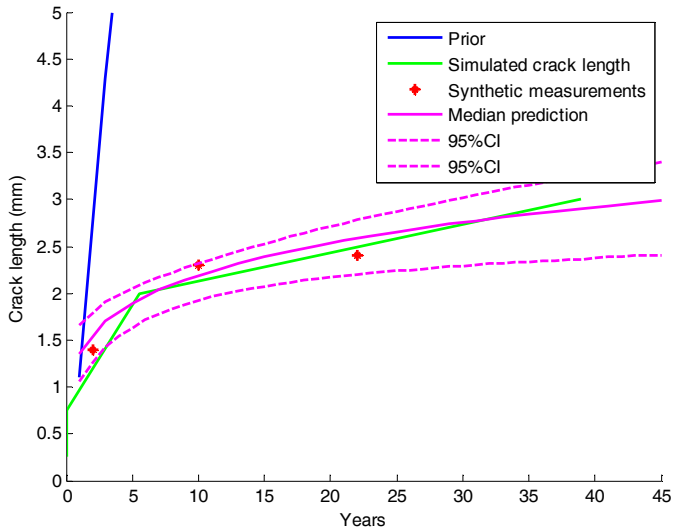


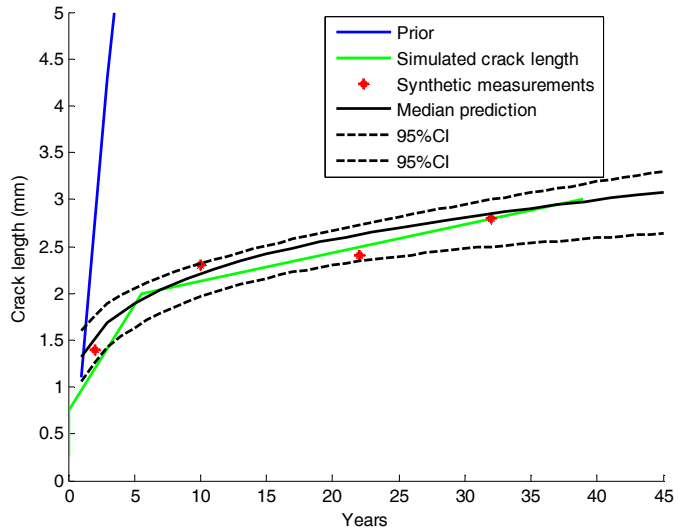
Bayesian updating results - 1



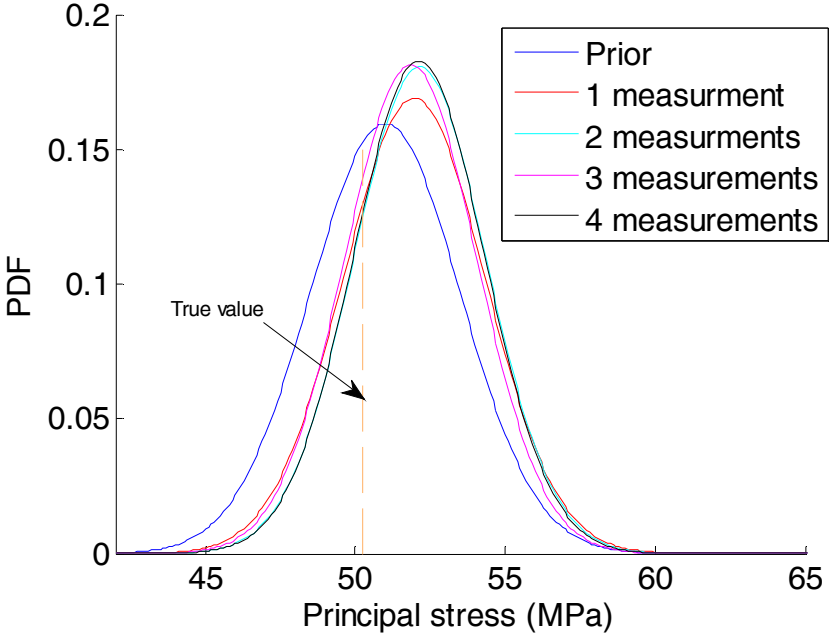


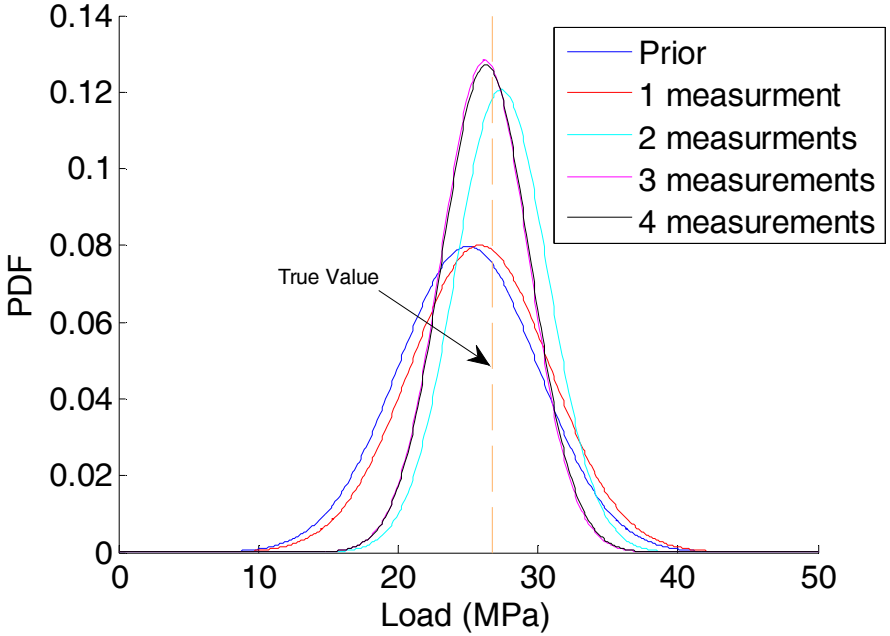
Bayesian updating results - 2





Posterior distribution of design variables





Future Program Improvements

- Enhance the visibility of pipeline research to university faculty and students
- Student travel budget to visit industry facilities and attend workshop/conference
- Reduce paperwork burden and the over all submission process
- Is your university open toward future CAAP awards?

  Yes

Project Reporting

- Final Reporting and any student poster papers are available from:

https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=508

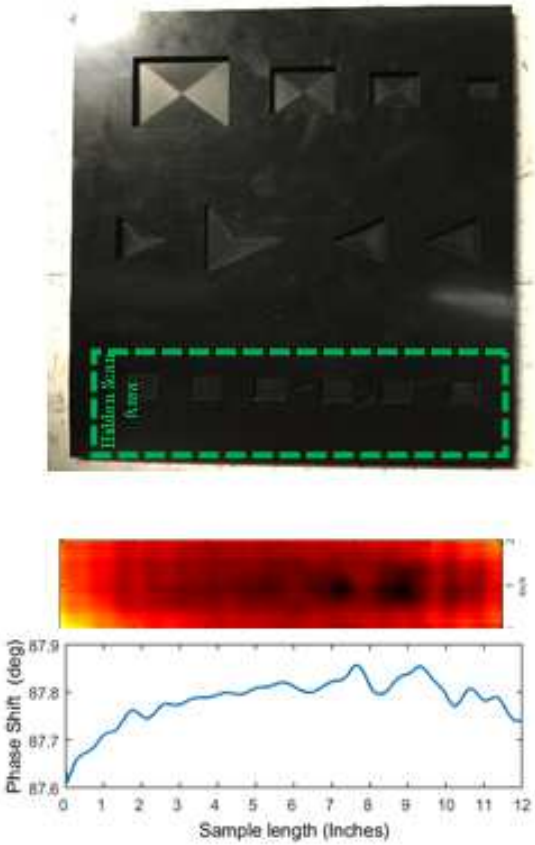
THANK YOU!

Appendix

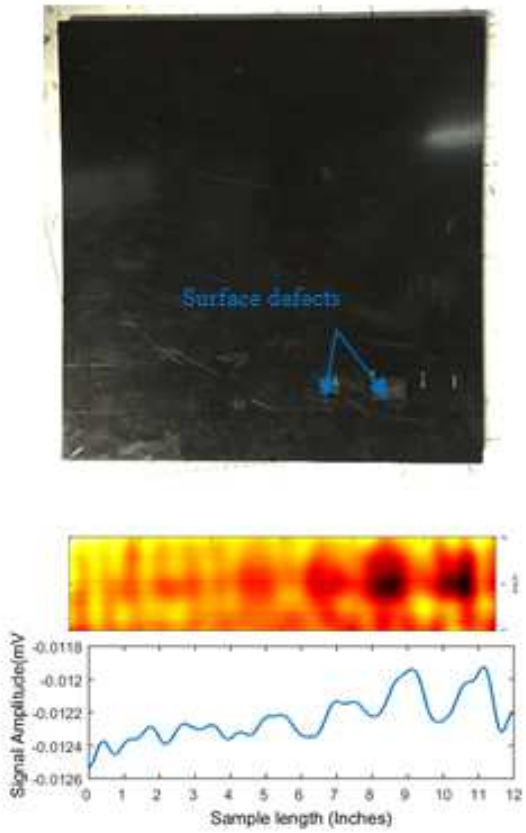
- More technical details are included in the appendix.

Sensitivity study: PA and PE Sample

- Phase vs. Amplitude for PE



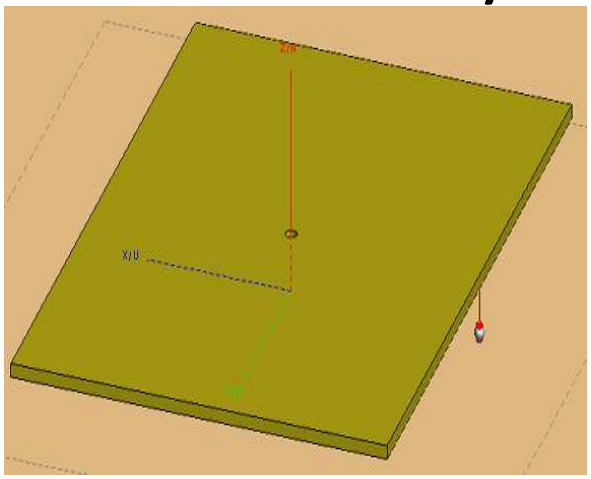
Phase Measurement



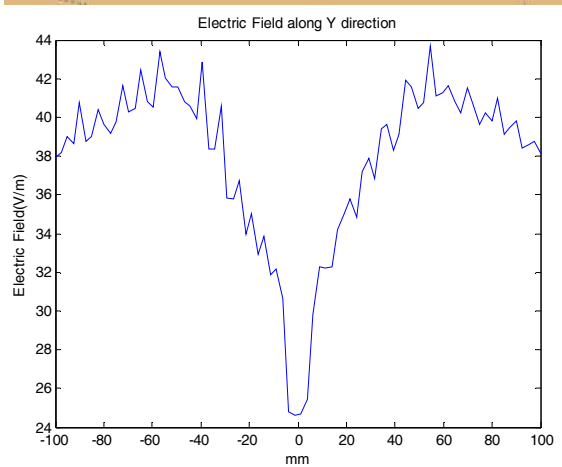
Amplitude Measurement

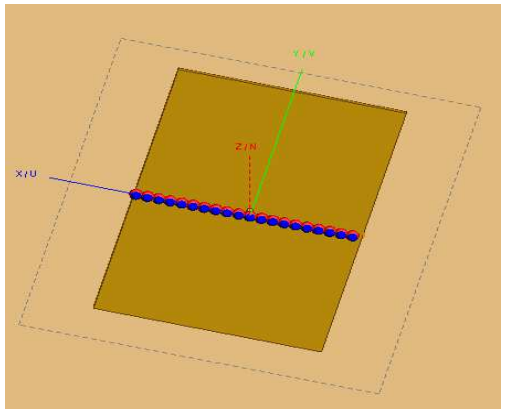
Simulation results: 1-D

- FEKO Linear array model



Simulation geometry
Center hole: 5mm
Plate size: 340mm x 486mm x 8mm
Material type: PA





Fundamentals of CS

$$\boldsymbol{f} = \boldsymbol{\Psi c} \qquad \text{...(1)}$$

where, vector $\boldsymbol{f}$ $(N \times 1)$ contains the samples of the original signal f(t)
$\boldsymbol{\Psi}$ is sparsifying matrix (N x N)
$\boldsymbol{c}$ is sparse representation of $\boldsymbol{f}$

$$\boldsymbol{y} = \boldsymbol{\Phi f} \qquad \text{...(2)}$$

where, $\boldsymbol{\Phi}$ is measurement matrix (M x N) and (M<<N)

Vector $\boldsymbol{y}$ contains acquired samples corresponding to the measured signal y (t) (M x 1)

By combining equations (1) and (2)

$$\boldsymbol{y} = \mathbf{A}\boldsymbol{c} \qquad \text{...(3)}$$

where, A is $\boldsymbol{\Phi\Psi}$

Equation (3) is solved for $\boldsymbol{c}$ by basis pursuit or matching pursuit algorithms.

Matrix Design: Restricted Isometry Property and Incoherence!

Fundamentals of CS (contd.)

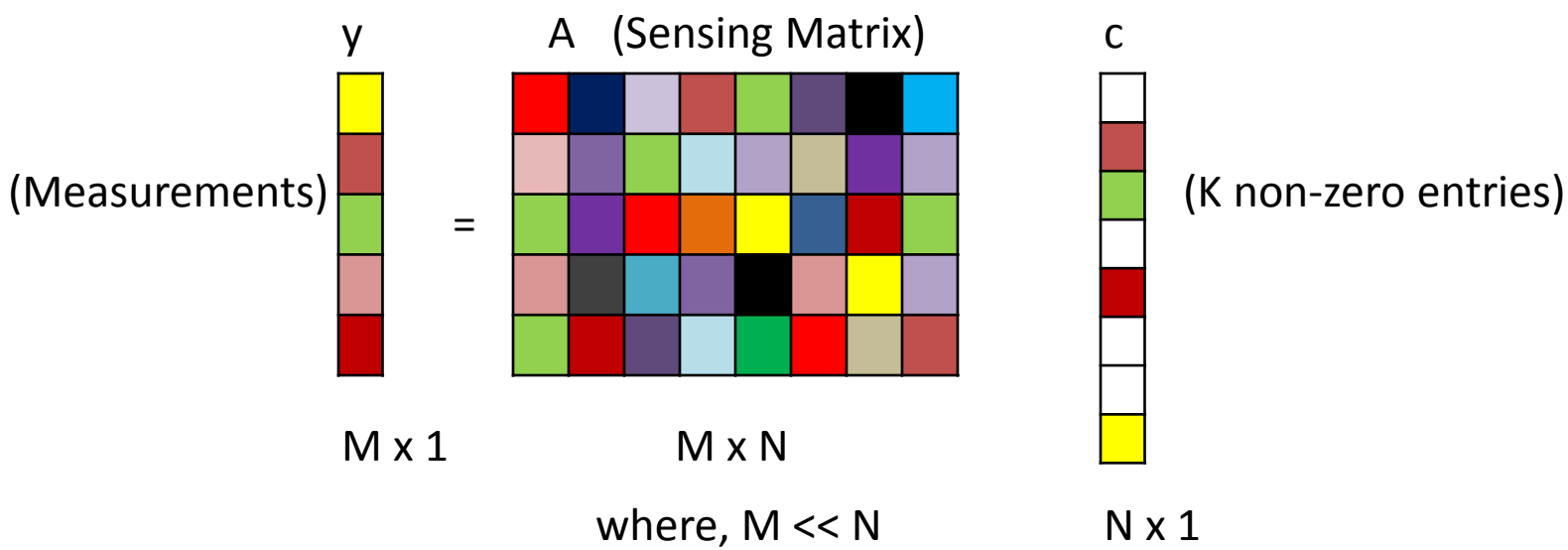


Fig. 7 Representation Sampling Equation

M > cKlog(N/K) (What is the lower bound of M?)

To reconstruct from under sampled set of data one need special reconstruction algorithms like:

- l1- minimization
- Orthogonal Matching Pursuit

Basis Pursuit Algorithm

- Theory: find c vector in translated null space

$$H = \text{Null}(A) + c$$

- l1- minimization is a basis pursuit algorithm to solve for sparsest decomposition of a signal.

$$y = Ac$$

l1- minimization techniques ask to estimate c equals to:

$$\text{argmin } \|c\|_1 \quad \text{...subject to } Ac = y$$

which, can be recast as linear program:

$$\min_c \sum_{n=1}^{N} |c(n)| \quad \text{...subject to } Ac = y$$

Orthogonal Matching Pursuit Algorithm

- Orthogonal Matching Pursuit(OMP) is a greedy algorithm in that at each iteration, it chooses the column from A that current approximates an orthogonal projection onto the space spanned by the columns selected so far.
- OMP guarantees to converge in ≤ N iterations, then we find our estimated solution for microwave image reconstruction:

$$\text{argmin}_c\{||y - Ac||^2\} \quad \text{...subject to } ||c_n|| < N$$

Proof of concept with 1-D signal

- One Dimensional signal is taken into process to check the applicability of CS with near field signals.
- Single row is scanned over object having through damage. (represented by f(t))

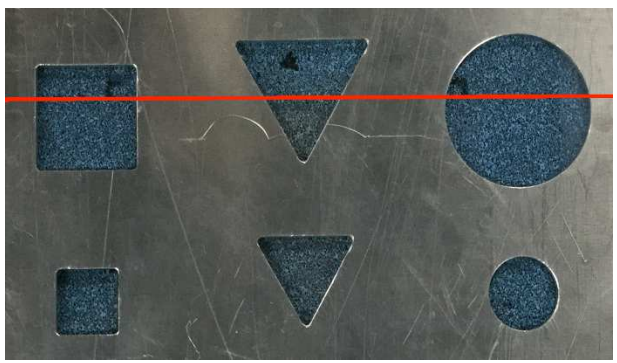


Fig. 8 Sampling single row of object

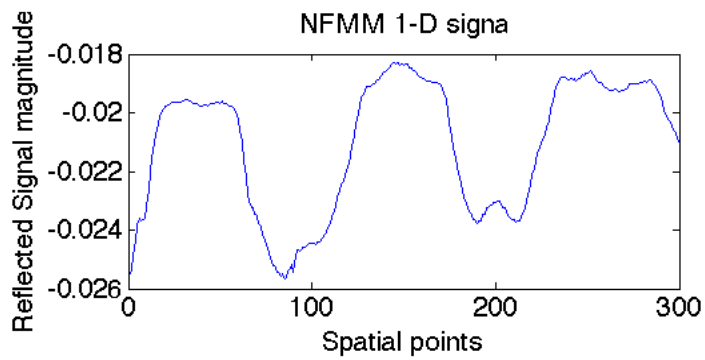


Fig. 9 Reflection coefficient plot

Proof of concept with 1-D signal

- Signal f(t) is sparse in DCT domain.
- NF signal satisfy the CS requirement to get randomly sampled.
- Sparse signal is represented as c(n).

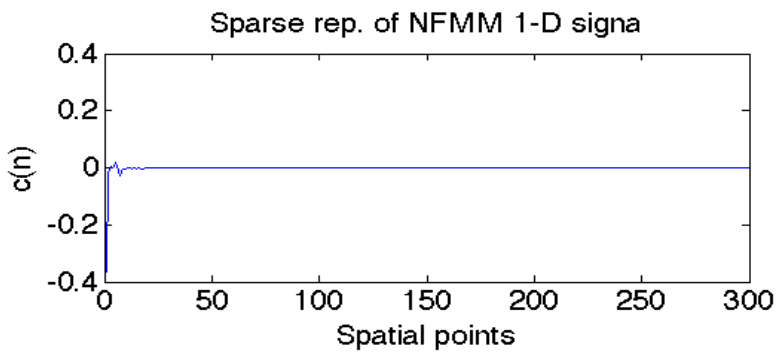


Fig. 10 DCT of f(t)

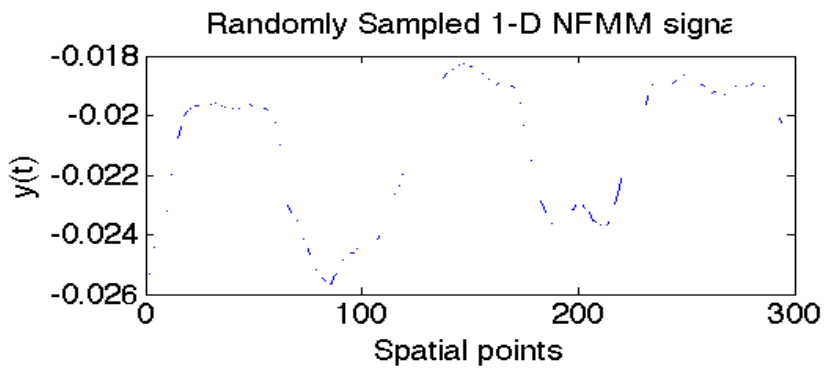
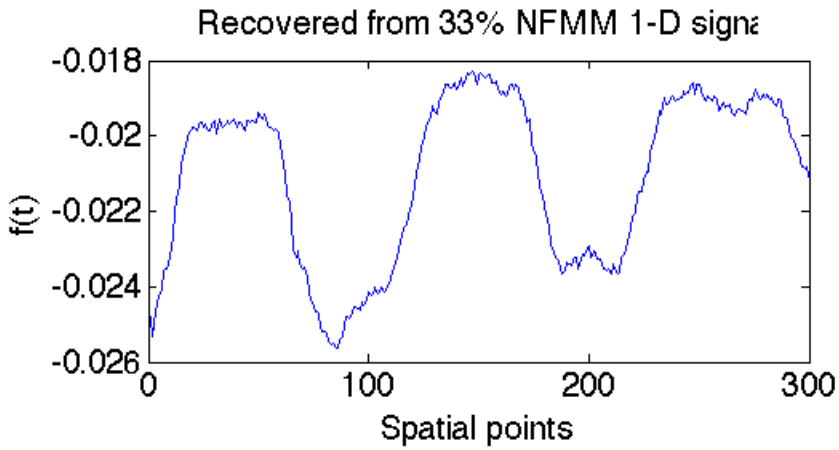


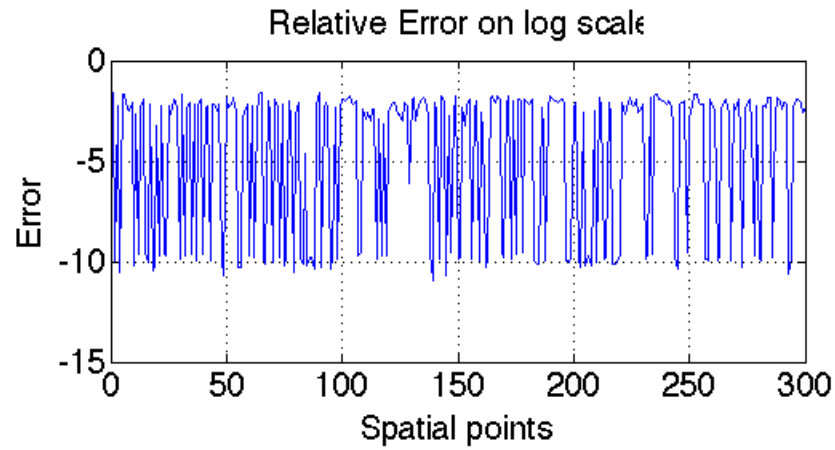
Fig. 11 100 random samples of f(t)

- Signal f(t) is sampled at only 100 spatial points (33%).
- Sparsely sampled signal is represented as y(t).

Proof of concept with 1-D signal

- l1- minimization technique is used to estimate the original signal from random samples.
- Recovered signal is represented as rf(t).





- rf(t) plot shows the good estimation of original signal f(t).
- Relative error on log scale is shown.

Changes in NFMM setup (contd.)

- In Fig.14 red line represents the scanned rows and blue line represents the skipped rows.
- Now each column is randomly sampled at sub-nyquist rate and gives under sampled representation of original signal.
- Each column is treated as 1-D signal and l1-minimization technique is applied to generate 2-D image.

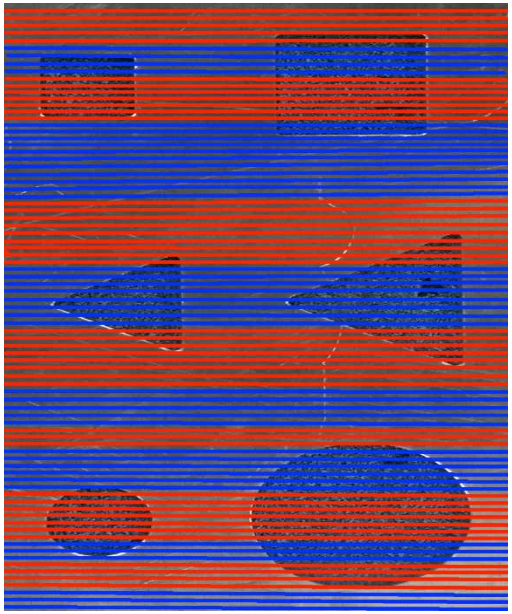


Fig. 14 Sampling setup

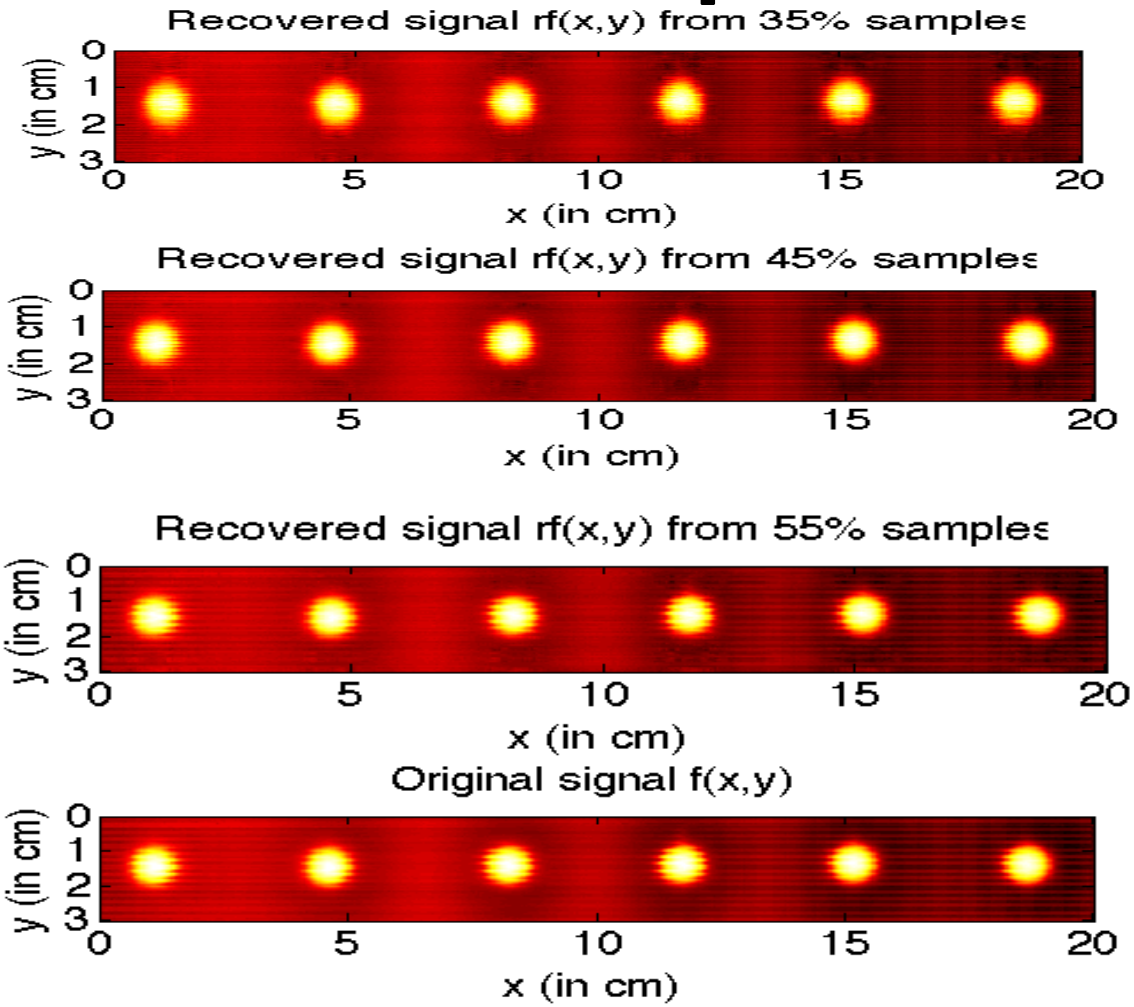
2-D Results

- Aluminum plate (190 mm x 100 mm) with different shape and size of cracks is scanned keeping 0.635mm step size.
- Plastic plate (230 mm x 230 mm) is scanned keeping 0.635mm step size.
- Aluminum plate (200 cmx 25 mmm) with circular holes and radial crack is scanned keeping 0.5mm step size.

Discussion

- Fig. 18, 19 and 20 shows the recovered 2D images from 35%, 55% and 45% samples respectively.
- Scanning time for Fig. 18 is 2.8x faster than previous results.
  - Additionally number of spatial locations are reduced to 16,800 and collected number of samples are 50.4 millions .
- Scanning time for Fig.19 is 1.8x faster than 100% scan.
- Scanning time for Fig.20 is 2.2x faster than 100% scan.

Additional Experiment (contd.)



PSNR= 74.33
Time= 16.83s

PSNR= 78.77
Time= 18.74s

PSNR= 79.96
Time= 18.03s

Original Signal