SH Wave EMAT for In-line NDI of Pipelines

Final Debriefing

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Intelligent Automation, Inc.
G. Zhao, B. Ayhan, G. Mei and C. Kwan

Oak Ridge National Laboratory
Venugopal K. Varma

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1. Overview of the Phase 1 Project

- **Problem Statement**

a) Mechanical damage is the single largest cause of failure in pipelines

b) Mechanical dents can be divided into “Cup” dents which are safety critical and “Saucer” dents which are usually benign.

c) An in-line inspection tool is needed that is tolerant to unpredictable sensor behavior introduced by the pipe thickness change and surface deformation

d) Advanced signal detection and classification algorithm is required for a yes-or-no indication of the presence of defect, defect type and sizes

• Phase 1 result summary

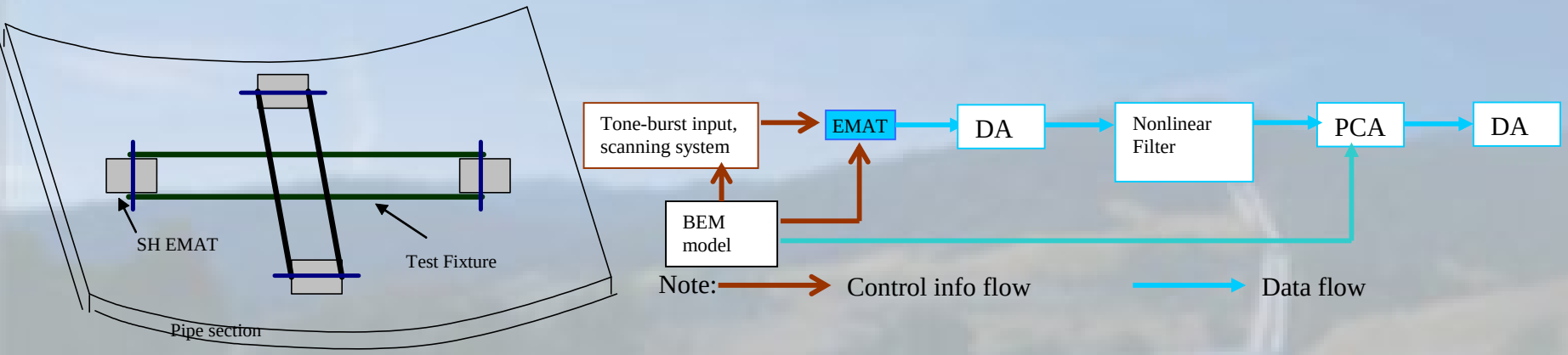


Fig. 1 Architecture of the proposed in-line pipe inspection system

Phase 1 Results

Theoretical Developments
- Applied BEM to defect analysis

Algorithms implemented
- SID
- OSP
- NCLS
- PCA-DA

Experiments
- Notch crack data
- Two 12'' pipe data sets with "Cup" and "Saucer" dents

Extensive simulations
- Applied many algorithms to the experimental data

GUI
- Demo the performance of PCA-DA for defect classification

Fig. 2 Summary of Phase 1 results

2. Mechanical dents specimen preparation

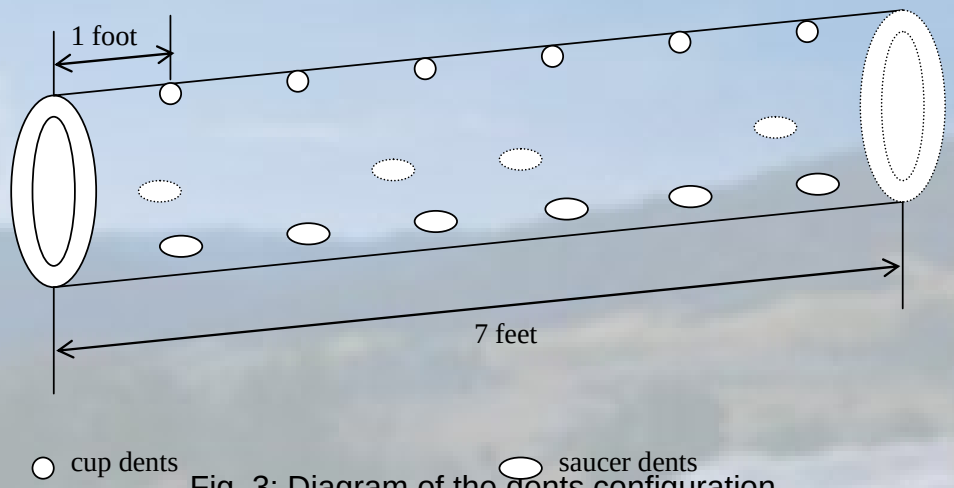


Fig. 3: Diagram of the dents configuration

A “cup” dent created with a 0.75” diameter ball

A “saucer” dent created with a 5” diameter ball

Table 1 Dent number and size information (in inches)

Dent Number	Diameter		Depth	Area of deformation	Ball Diameter
	Axial	Circumferential			
1	0.395	0.378	0.085	0.63 x 0.55	0.75
2	0.5	0.488	0.218	1.4 x 0.75	
3	0.444	0.435	0.124	0.95 x0.75	
4	0.415	0.415	0.065	0.625 x 0.625	1
5	0.545	0.534	0.20	1.35 x1.2	
6	0.386	0.375	0.062	0.55 x 0.51	
7	0.72	0.65	0.033	1.25 x 0.875	3.75
8	1.35	0.995	0.118	3 x 3	
9	0.595	0.526	0.04	1.25 x 0.95	
10	1.46	0.855	0.134	2.4 x 1.56	5
11	1.46	0.894	0.121	1.6 x 1.3	
12	0.73	0.715	0.094	1.1 x 1.1	
13	0.615	0.547	0.070	0.95 x 0.65	3.75
14	0.875	0.775	0.179	1.75 x 1.3	3.75
15	0.886	0.75	0.123	1.5 x 1	5
16	0.745	0.62	0.076	1.1 x 0.85	5

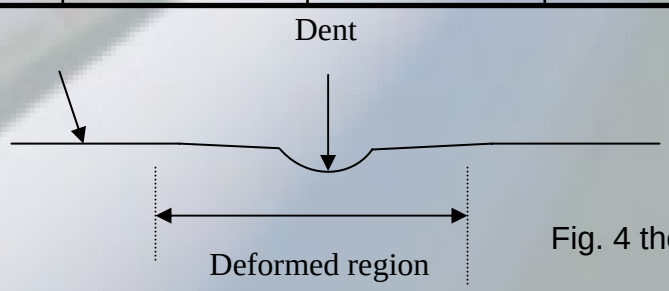


Fig. 4 the dent induced deformation

3. Guided SH wave EMAT Inspection Technology

- **Theoretical Modeling**
  - ✓ Wave modes that can propagate long distances in pipes
  - ✓ Wave structure analysis for best sensitivity to the defects
  - ✓ Physical based feature selection such as scattering profiles from the defect

2-D Boundary Element Modeling

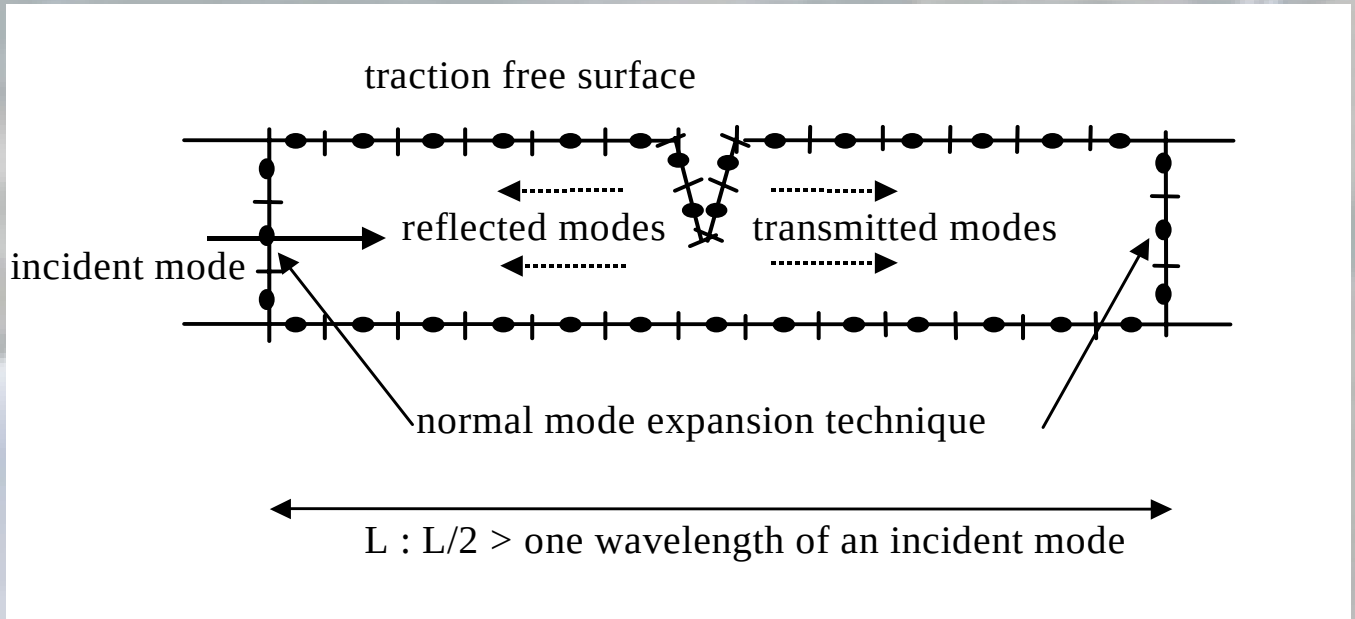
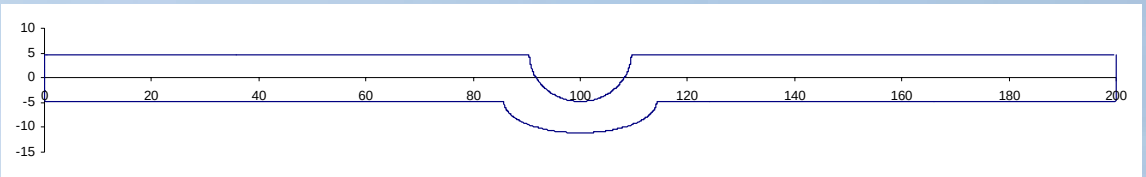
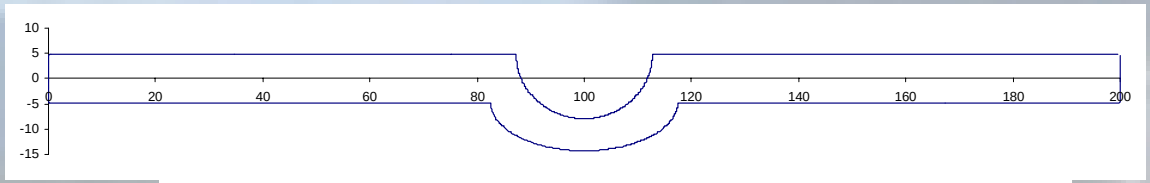


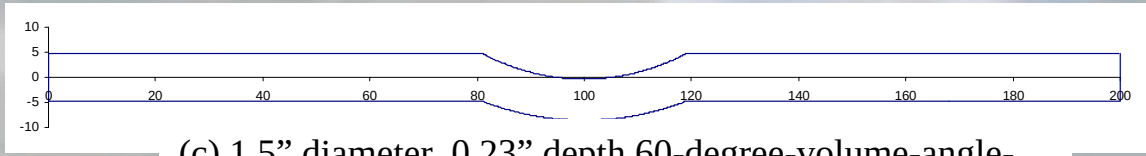
Figure 5: Boundary element model for guided waves interaction with a surface–breaking defect



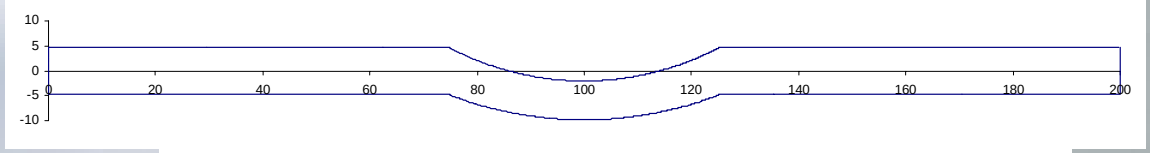
(a) 0.75” diameter, 0.375” depth half-sphere “cup” dent



(b) 1” diameter, 0.5” depth half-sphere “cup” dent



(c) 1.5” diameter, 0.23” depth 60-degree-volume-angle-“saucer” dent



(c) 2” diameter, 0.31” depth 60-degree-volume-angle-“saucer” dent

Figure 6: BEM model of the “cup” and “saucer” dents

• Calculated Transmission and Reflection Coefficients for SH Waves Incident into the Dents

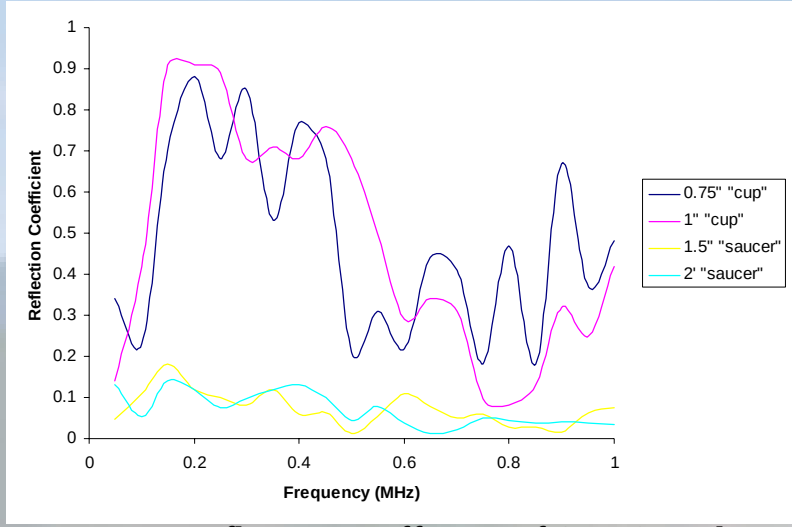


Figure 7: Reflection coefficient of SH n0 mode

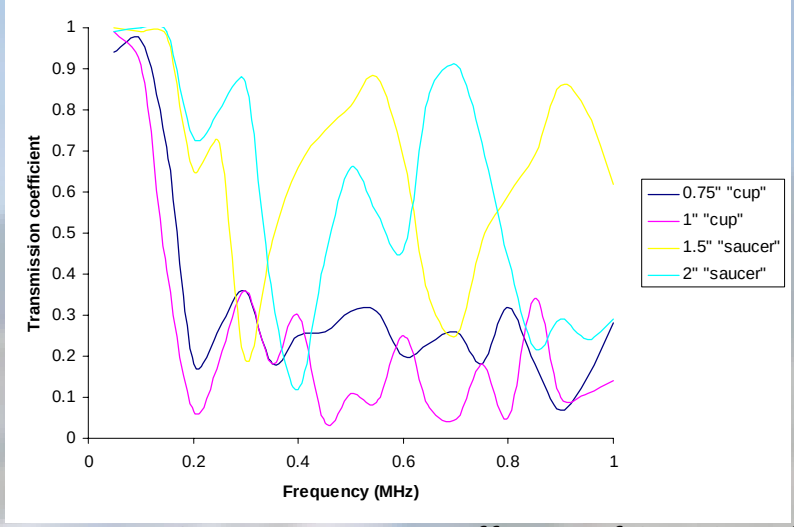
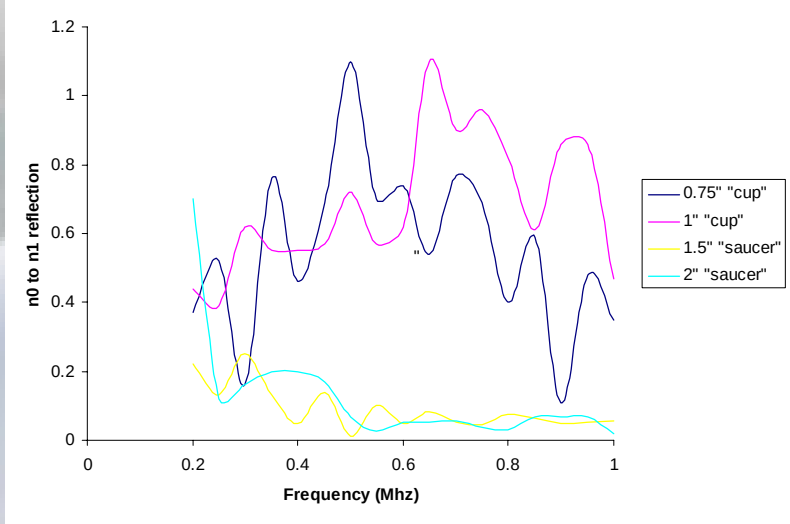


Figure 8: Transmission coefficient of SH n0 mode



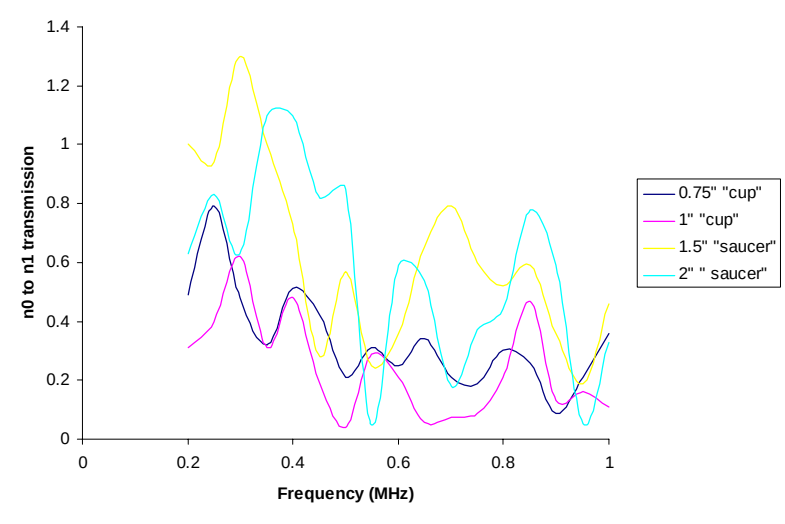
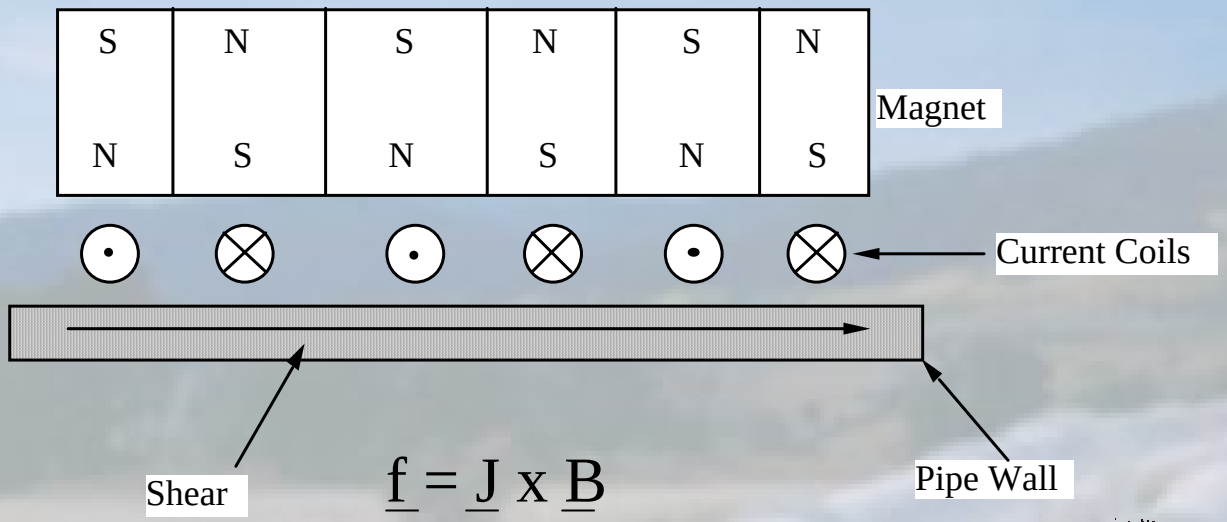


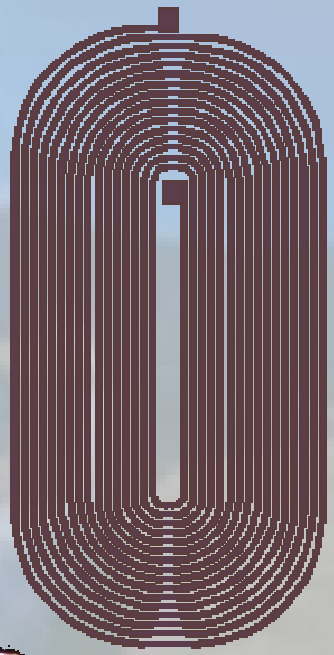
Figure 9: (a) Reflection and (b) transmission coefficient of the mode converted n1 mode for n0 mode SH wave incident into the dents

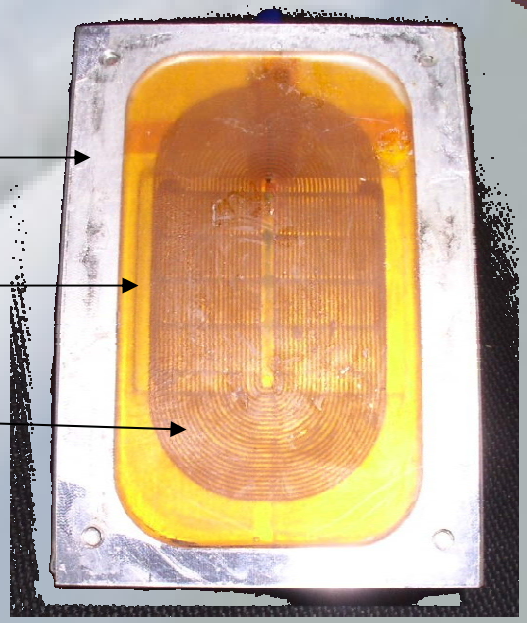
- It is evident that the dent will cause wave reflection and transmission energy partition
- SH wave at low frequency region (200 kHz ~ 400 kHz) has distinct response to “cup” dents and “saucer” dents
- Mode conversion occurs at the defect. n0 mode SH wave incidence will not only result in n0 mode reflection and transmission, but also n1, n2, or even higher mode to appear. This feature, though complex, could benefit for the defect classification and sizing since different dents will cause different response.
- More rigorous three dimensional modeling would depict the scattering profile along the circumference direction

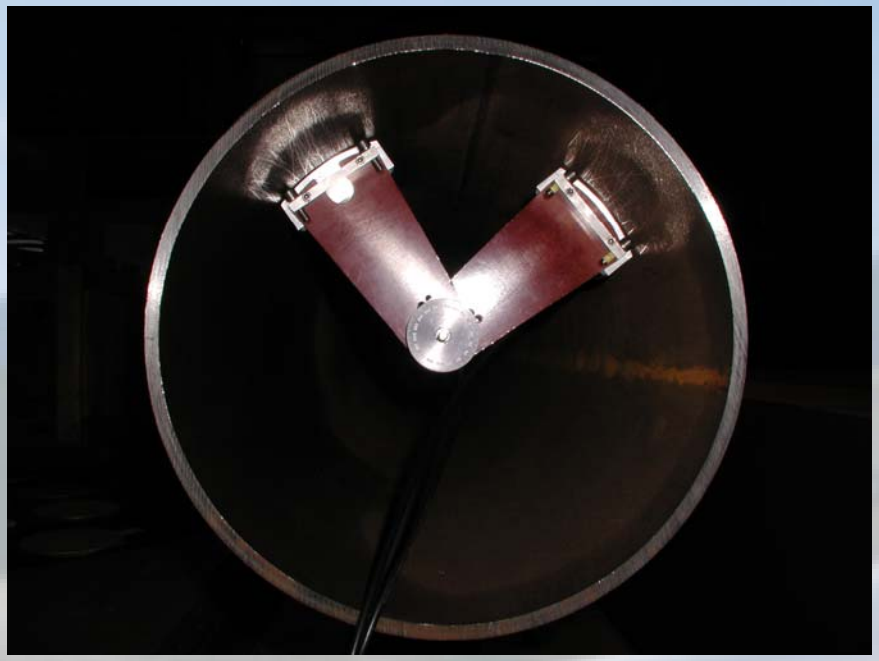
- **EMAT Sensor Design and Setup**



$$\underline{f} = \underline{J} \times \underline{B}$$



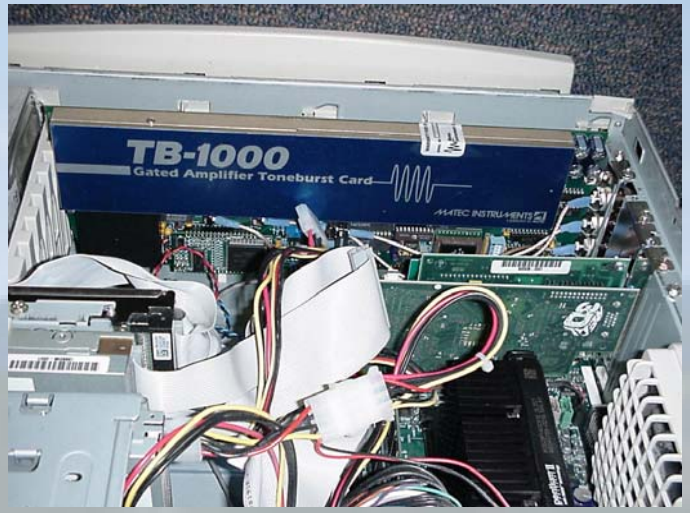




Circumferential EMAT Transducer-Receiver

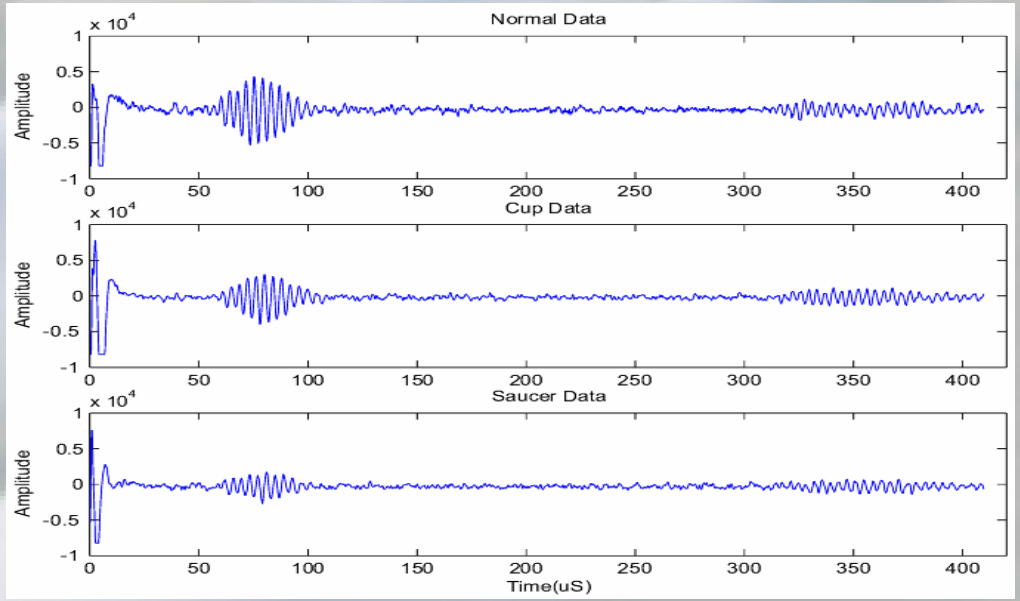
Test set-up

• Data Acquisition



PC based ultrasonic tone-burst generator and high speed digitizer

EMAT sensor system produced at IAI



Typical waveform in a pipe

4. Mechanical Dent Detection with Correlation Analysis

The correlation value is calculated by the following procedures:

(1) Use the first normal scan as the reference sample.

(2) For any new sample, shift it in the time domain so that the correlation value

$$\sum_{i \in Mainlobe} \mathrm{Re}\, f_i \bullet NewSample_i$$ is maximized.

(3) The outcome correlation value is recorded as this new sample to the reference sample

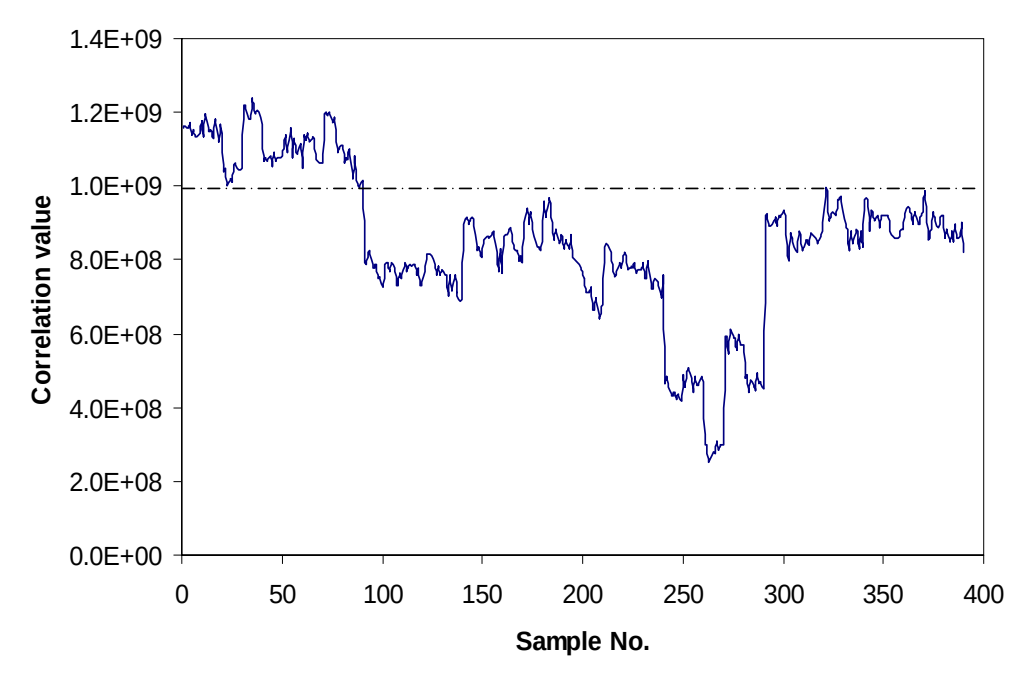


Figure 10: Time domain correlation value for the normal condition, cup dents and saucer dents. The first 90 samples are for normal conditions. The threshold is shown as a dash-dot line

Table 2 Results for the testing data sets regarding the Normal/Defect classification.

	Number of samples	Labeled as Normal	Labeled as Defect	Accuracy
Normal	80	80	0	100%
Defect	300	0	300	100%

- **Dent detection on the second pipe specimen**

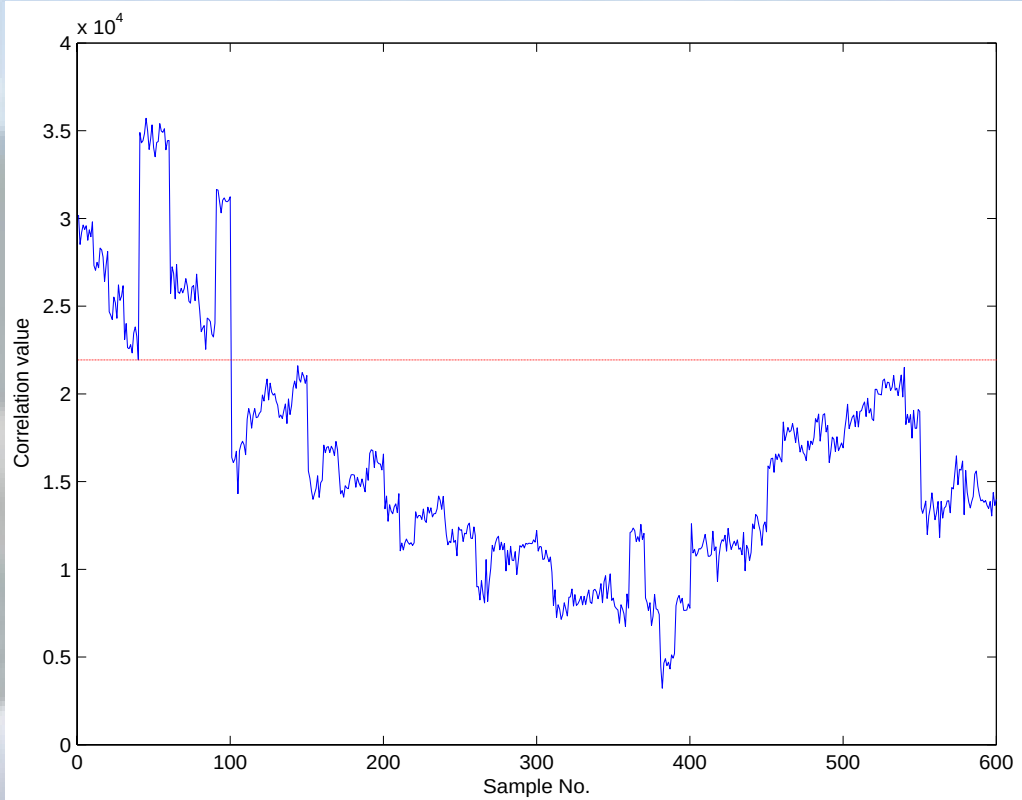


Fig. 11: Correlation value of all samples from new data set

Table 3. Results for the testing data sets regarding the Normal/Defect classification.

	Number of samples	Labeled as Normal	Labeled as Defect	Accuracy
Normal	90	90	0	100%
Defect	500	0	500	100%

5. Mechanical Dents Classification with PCA-DA Analysis

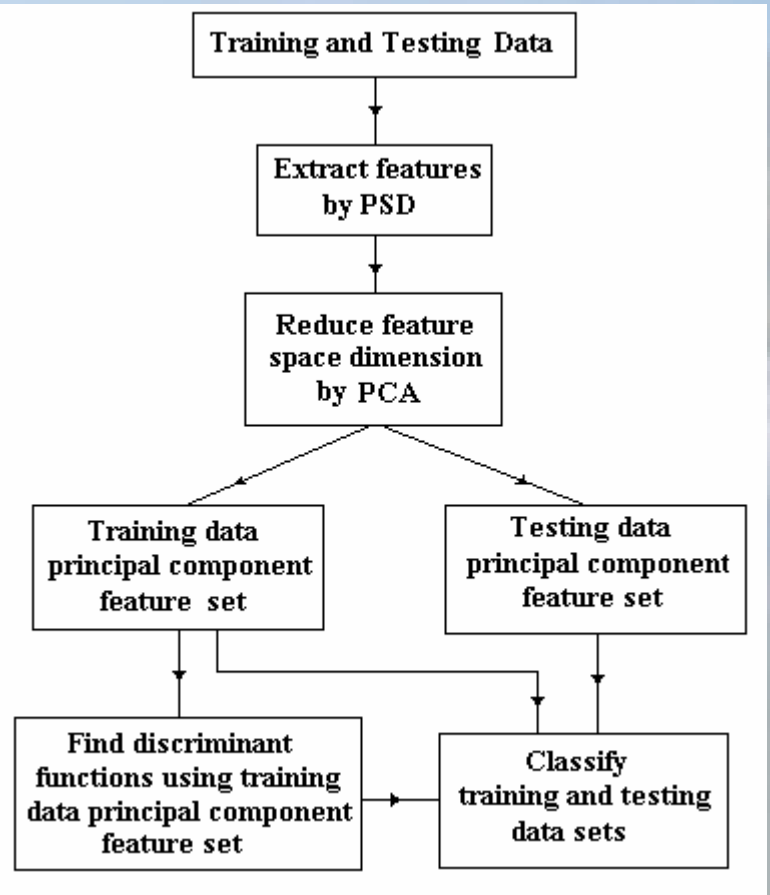


Figure 12: Block diagram of the PCA-DA based classification method.

• Dents classification in specimen #1

The data set has been divided into two sets:

- Training data set, (100 Cup, 100 Saucer),
- Testing data set (50 Cup, 50 Saucer).

A total of 14 principal component features have been used. Results for the testing data sets regarding the Cup/Saucer classification is shown in Table 4.

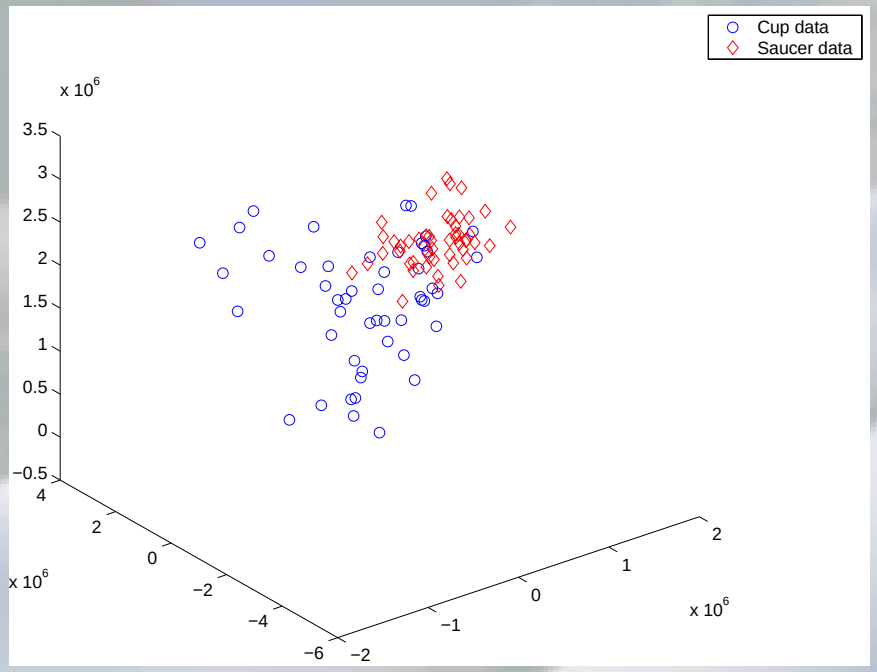


Fig. 14 PCA features of the dent data from specimen #1

Table 4 Results for the testing data sets regarding the Cup/Saucer classification.

	Number of samples	Labeled as Cup	Labeled as Saucer	Accuracy
Cup	50	50	0	100%
Saucer	50	17	33	66%

- **Dents classification in specimen #2**

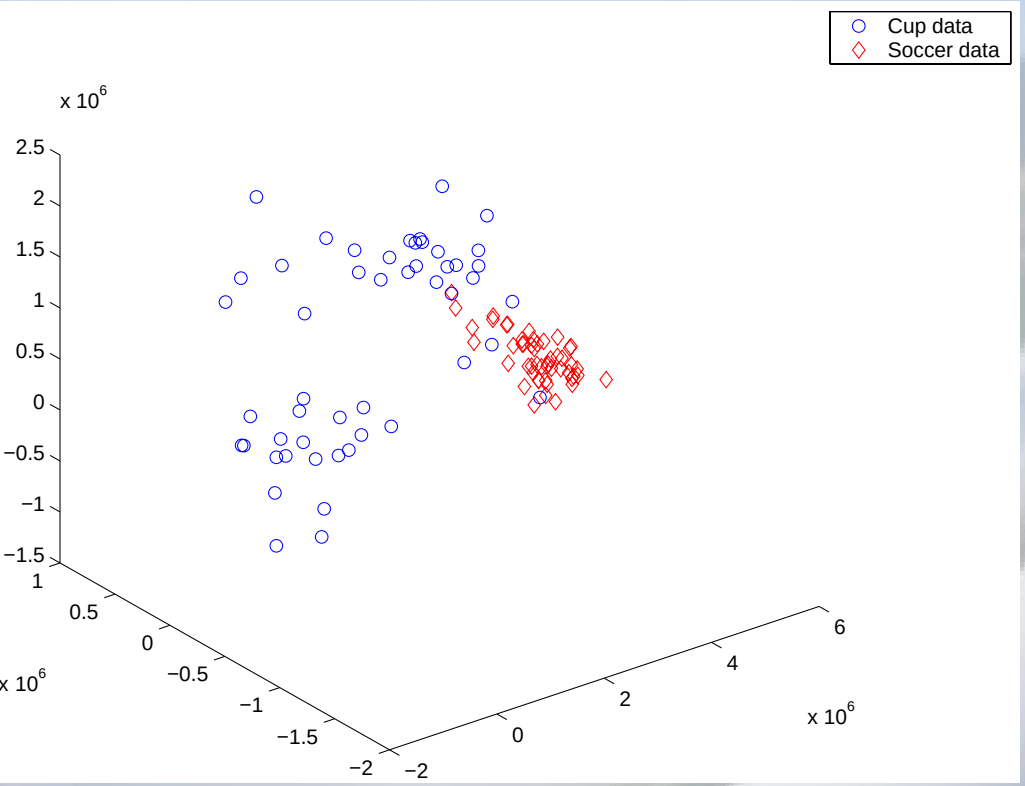


Fig. 15: PCA features of defect data.

Table 5 Results for the testing data sets regarding the Cup/Saucer classification.

	Number of samples	Labeled as Cup	Labeled as Saucer	Accuracy
Cup	50	48	2	96%
Saucer	50	15	35	70%

- **Dent depth estimation potential**

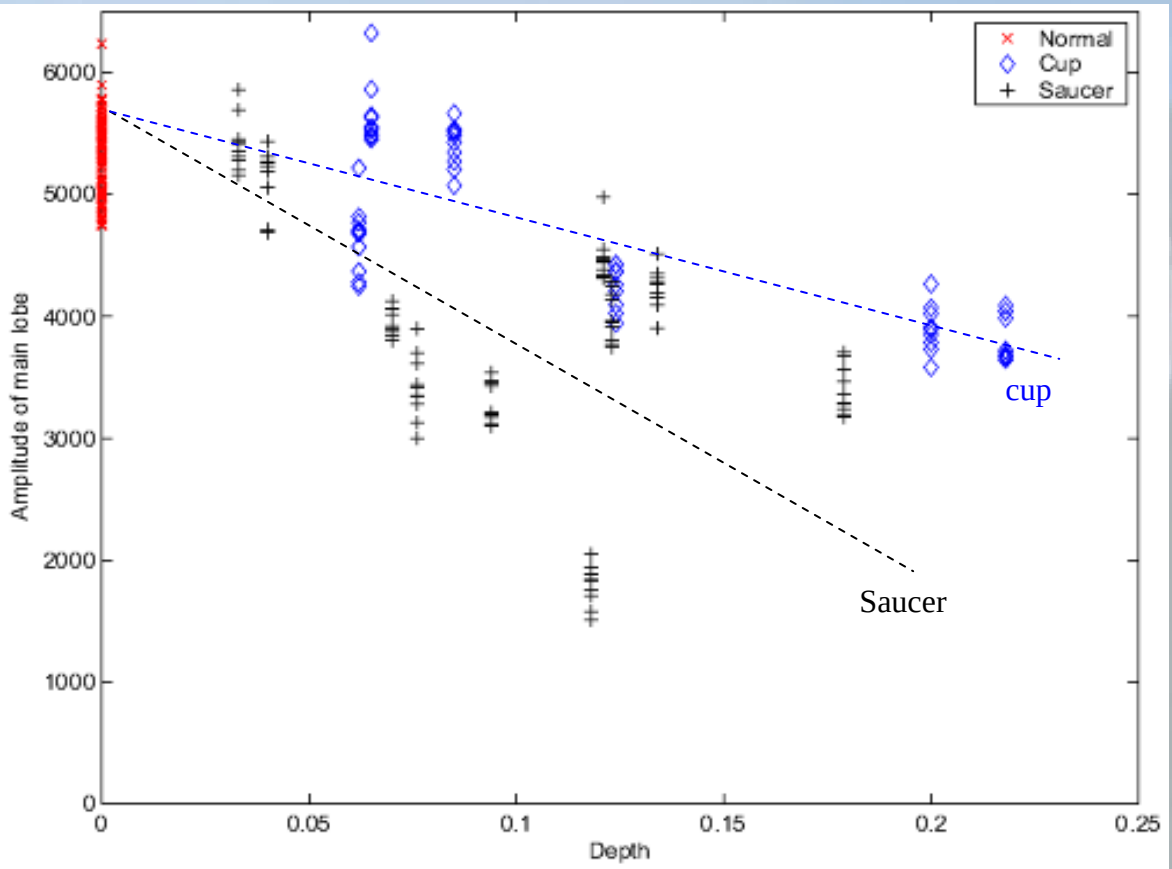


Fig. 16 EMAT through-transmission signal amplitude versus the dent depth showing the overall decreasing signal strength with deeper dents. Saucer dents experienced a relatively sharper decrease compared to the cups. This information can be used inversely to estimated the dent depth after “cup” and “saucer” separation

6. Graphical User Interface for Demonstrations

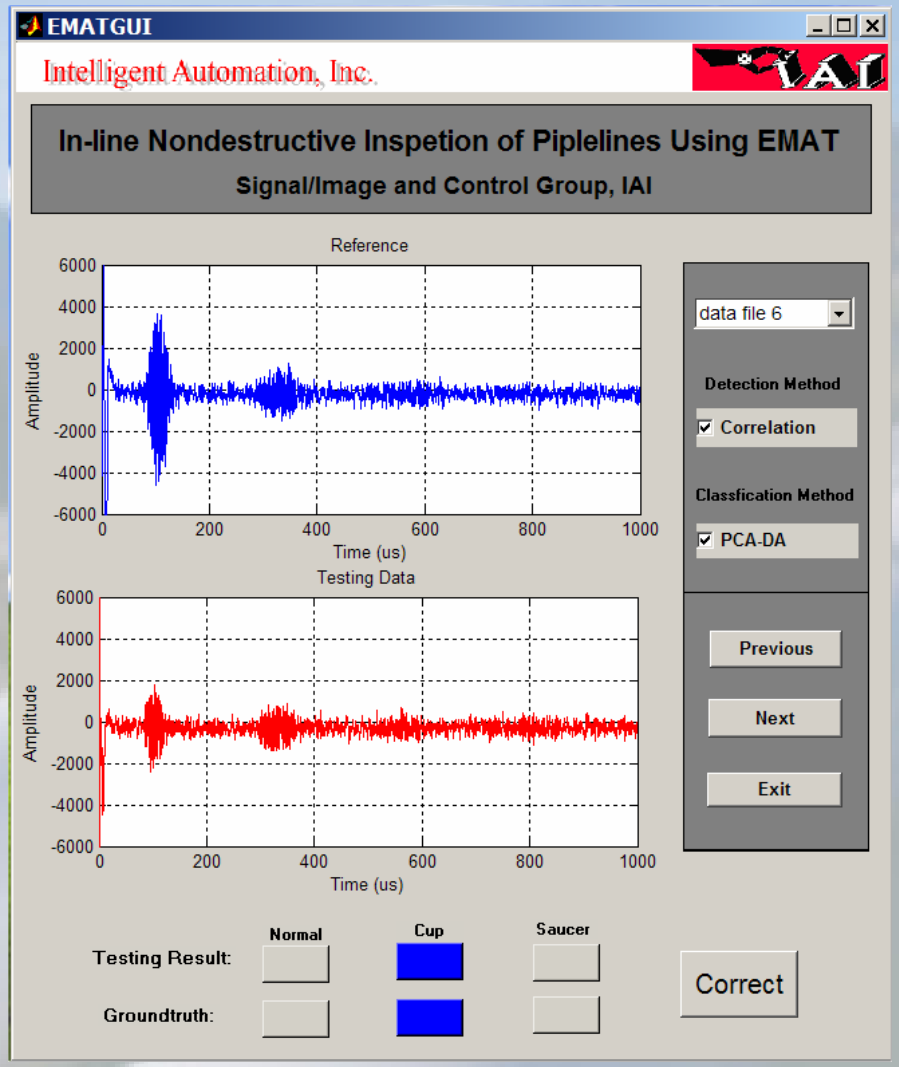


Fig. 17 GUI for pipeline dent defect detection and classification. (Click the graph for video)

7. Conclusions and Phase 2 Work Plan

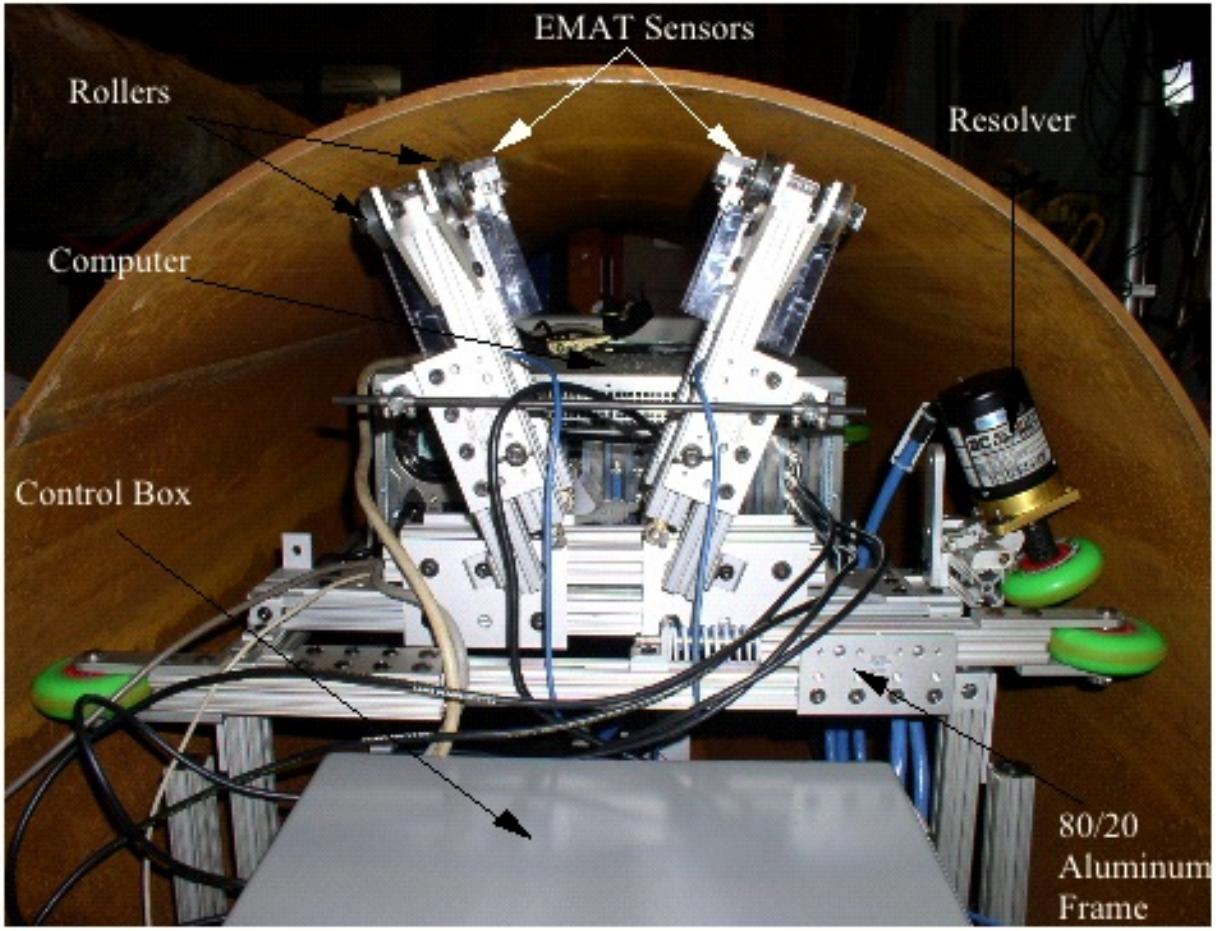
The proposed approach for detecting and classifying “cup” and “saucer” dents in pipes has been clearly demonstrated through extensive experiments and simulations. We have observed that:

- EMAT transducers are quite sensitive in detecting small dents (0.1”), which are much less that the minimum dent size (0.25”) required for safety repairs.
- Extensive experiments were performed to create dents with different sizes.
- Correlation analysis was used for defect detection. The performance was perfect.
- Four defect classification algorithms were implemented and evaluated. The PCA-DA was selected as a candidate for Phase 2 implementation. Our evaluation results showed that we can correctly classify over 95% of cup defects and near 70% of saucer defects.
- Initial theoretical developments based on Boundary Element Method showed that the frequency and mode information will be valuable for further improving the performance of defect detection and classification.

- **Phase 2 work plan**

1. Kick-off meeting
2. Theoretical model development. Instead of a 2-dimensional plane wave modal, 3-D guided wave model with the EMAT sensor characteristics will be setup for better accuracy.
3. Both the transmission line and distribution line will be studied for mechanical dents detection, classification and sizing.
4. Dent detection and classification when the EMAT is moving; Take consideration of the EMAT noises and pipe wall thickness changes.
5. Improve and optimize the diagnosis and classification algorithms; implement the algorithms in-real time hardware.
6. Prototype development of an automated in-line EMAT PIG.
7. Graphical User Interface development for PIG control and inspection results display.
8. Demonstration of the system at Oakridge lab and DOT

- **A baseline PIG system developed at ORNL**



ORNL PIG Inside a 30 inch Pipe

Acknowledgment

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