In-line NDI of Mechanical Defects in Pipelines with Shear Horizontal Wave EMAT

DOT/PHMSA Contract # DTRT57-06-C-10004
Final Debriefing

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Intelligent Automation Inc.

Company Overview

- Woman-owned small business
- Founded in 1987
- Located in Rockville, Maryland
- 93 professional staff; $15M revenue for 2005
- Specializes in R&D; Advanced artificial intelligence applications
- Highly qualified scientists, engineers, and programmers with extensive experience in advanced technologies; most with advanced degrees

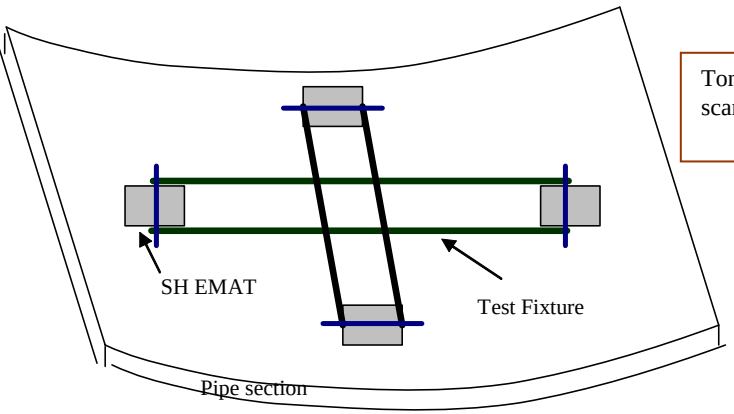
Core Technologies

- Control and Signal Processing
  - Health Monitoring, Noise Cancellation, Adaptive Control, Chatter Control
- Communications
  - Ultra wide Band Communications
- Distributed Intelligent Systems
  - Multi-agent Systems, Modeling and Simulation, Scheduling and Logistics, Collaborative Decision Making, Mobile Networks
- Sensors [DOD, NASA, BAE Systems, Raytheon]
  - New Sensing Technology & Validation, Sensor Network & Fusion
- Electromechanical Systems
  - Ballistic Analysis, Exercise Equipment (Space and physical therapy applications)
- Education Technology
  - Expertise: Simulation-based Training, Distance Learning, Educational Aids, Standards (SCORM/S1000D)

Project Overview

- Mechanical damage is the single largest cause of failure in pipelines; in-line inspection tools are needed for damage detection, localization, classification, and sizing, etc.
- "Cup" and "Saucer" types of mechanical dents
- Non-contact shear horizontal ElectroMagnetic Acoustic Transducers (EMAT) for circumferential and axial guided waves inspection of dents
  - Long range
  - Fast
  - Non-contact
  - Robust, highly repeatable
- Theoretical model for wave scattering from dents
- Accurate dent detection and classification algorithms for a yes-or-no indication of the presence of defect, recognizing defect type and sizes

Technical Approaches



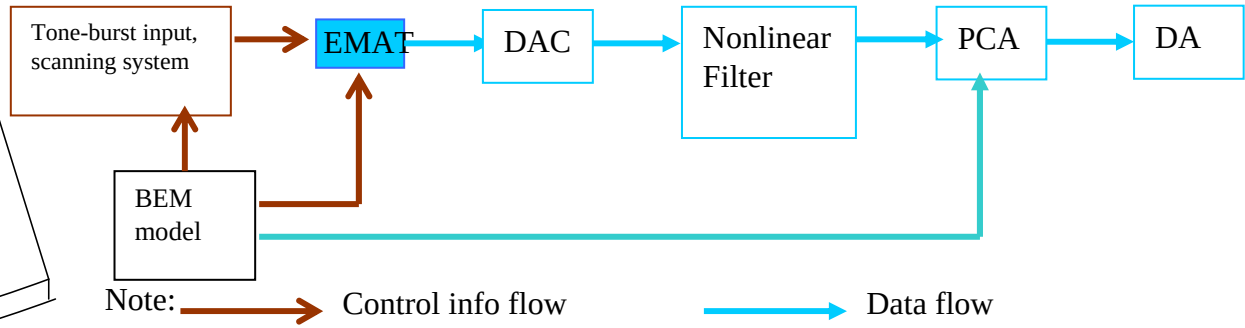
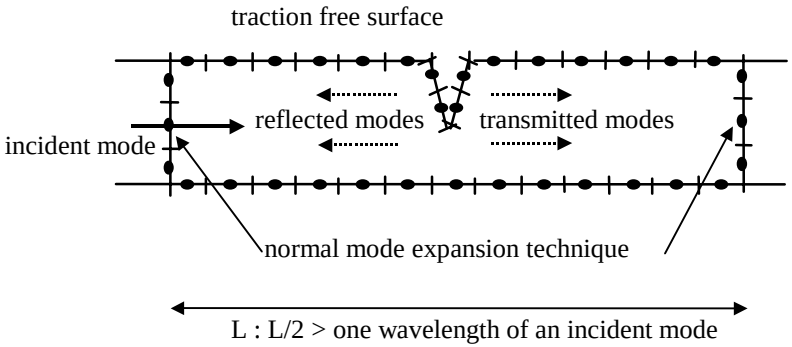


Fig. 1 Architecture of the proposed in-line pipe inspection system



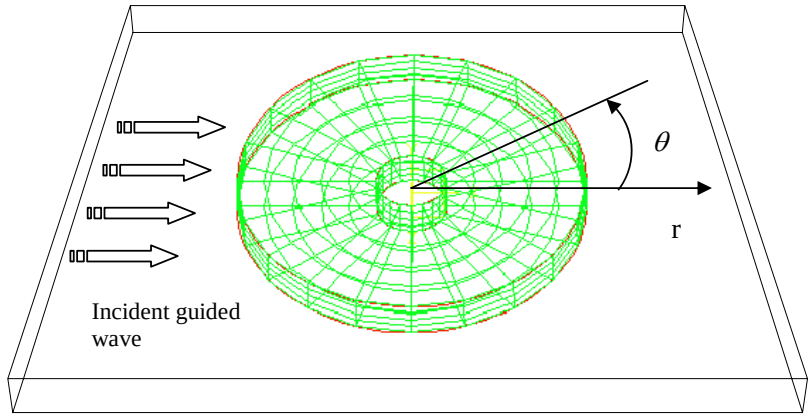
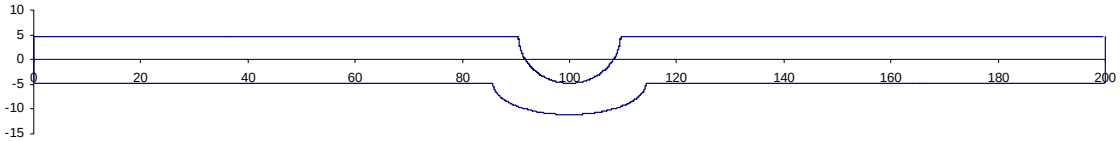
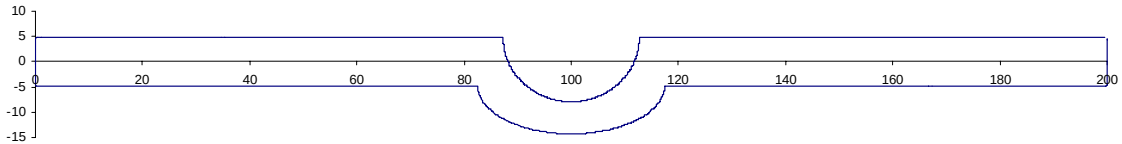


Fig. 2 2-D and 3-D BEM modeling

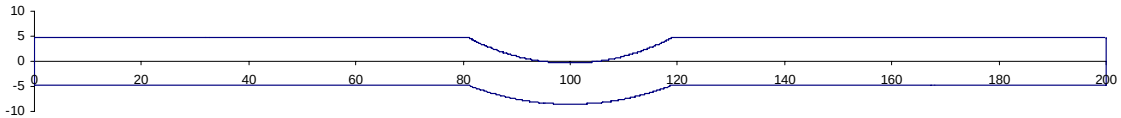
2-D BEM Results



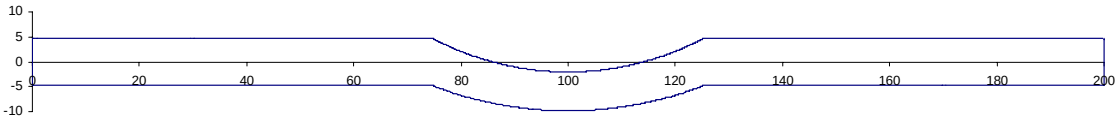
(a) 0.75” diameter, 0.375” depth half-sphere “cup” dent



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

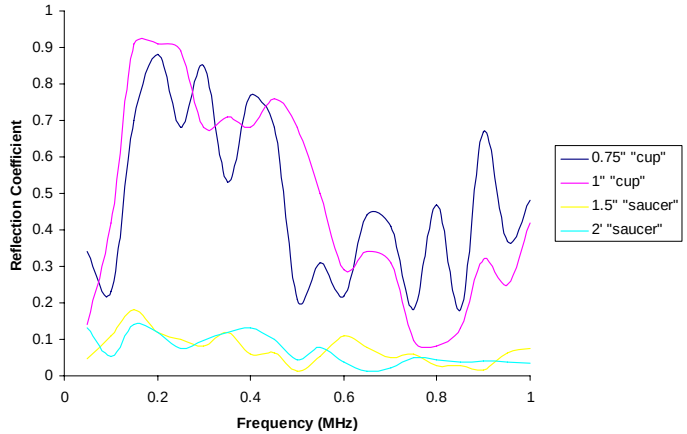


(c) 1.5” diameter, 0.23” depth 60-degree-volume-angle-sphere “saucer” dent

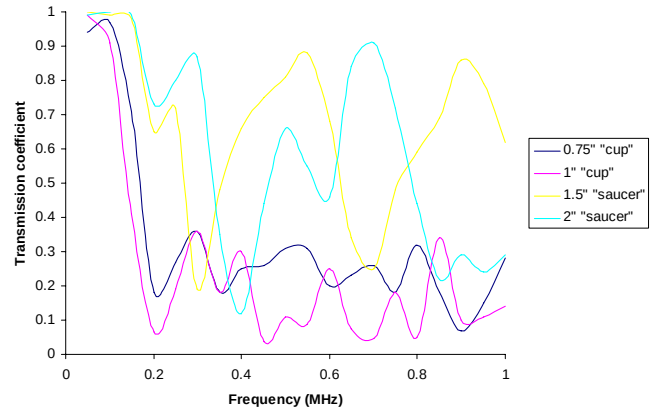


(d) 2” diameter, 0.31” depth 60-degree-volume-angle-sphere “saucer” dent

Note: SH wave around 200~300 kHz is sensitive to different types of dents

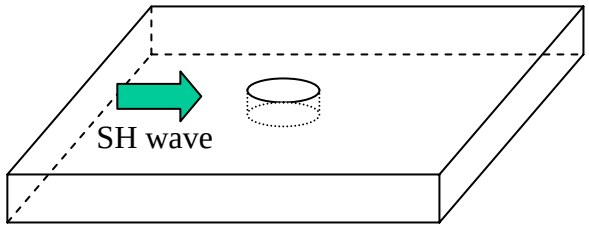


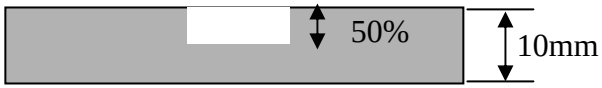
Reflection coefficient of SH n_0 mode wave incident into the dents

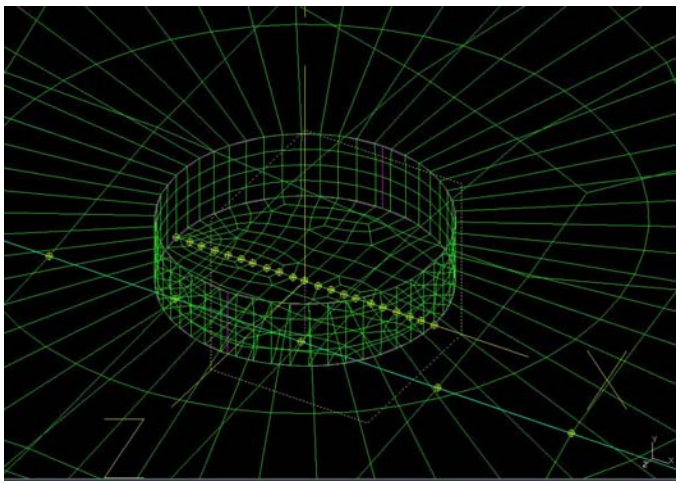


Transmission coefficient of SH n_0 mode wave incident into the dents

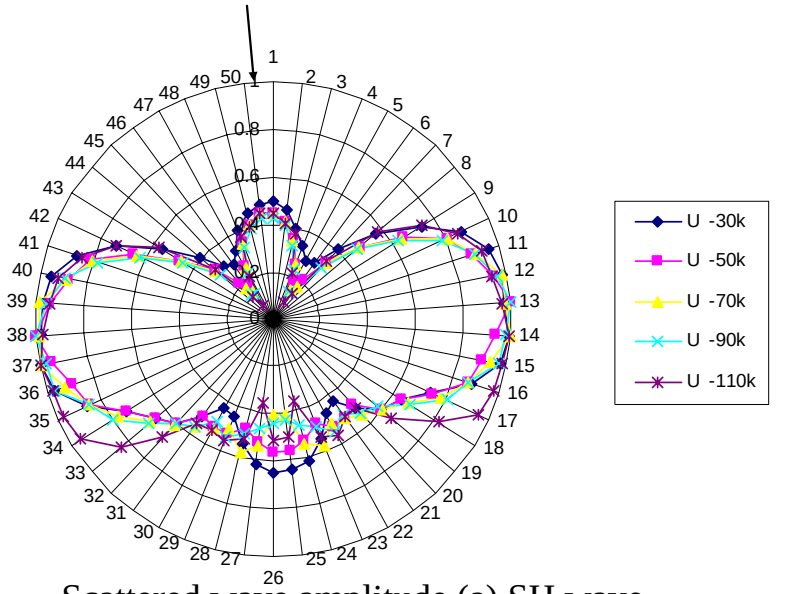
3-D BEM Results



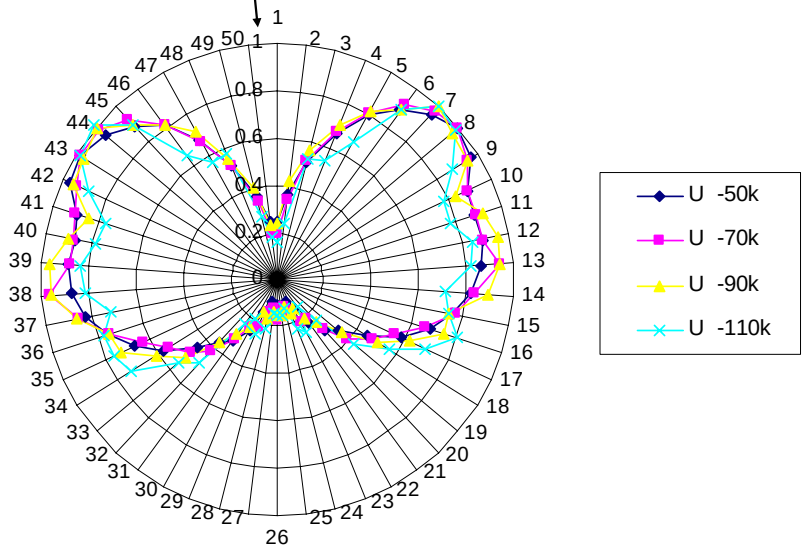




I-DEAL mesh



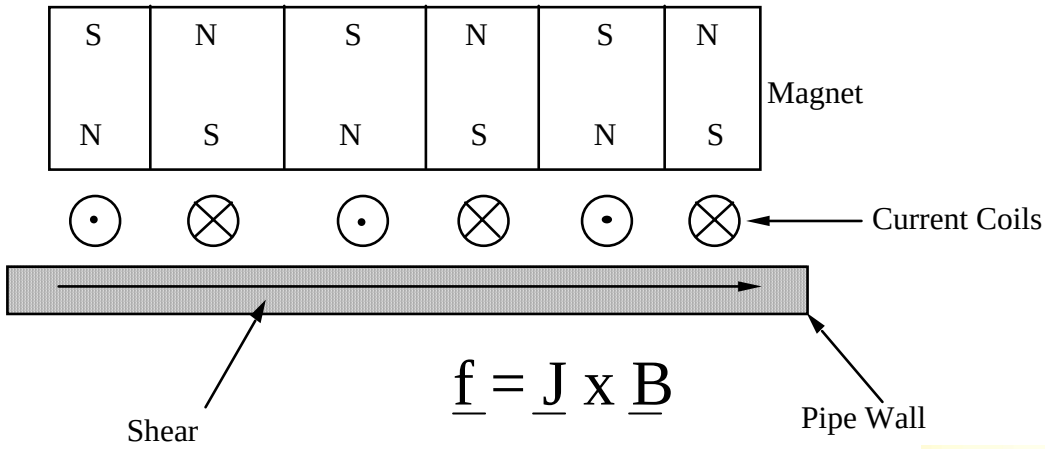
Scattered wave amplitude (a) SH wave

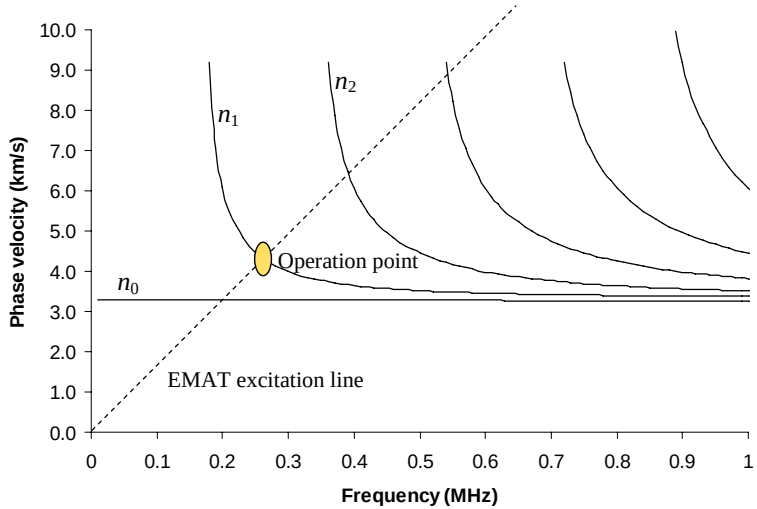


Scattered wave amplitude (b) Mode converted Lamb wave

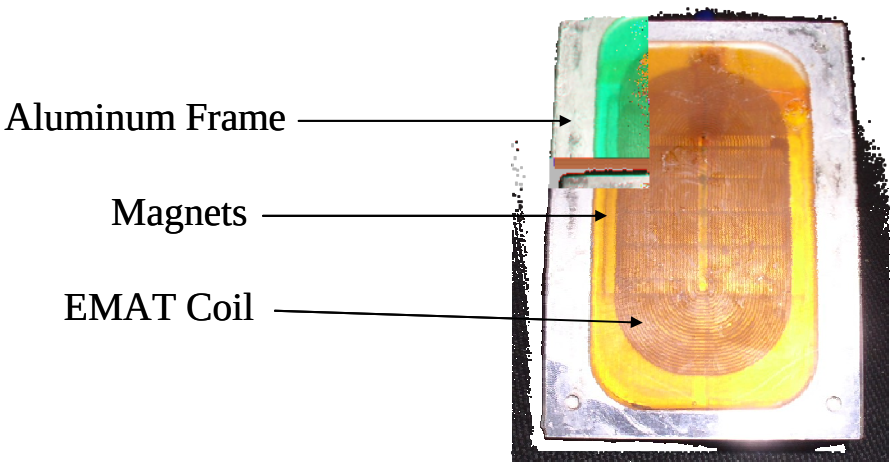
EMAT Sensor Design

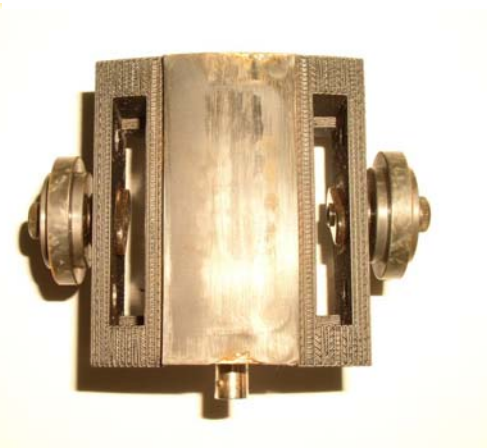
Lorentz Force EMAT principle





SH wave Dispersion curve

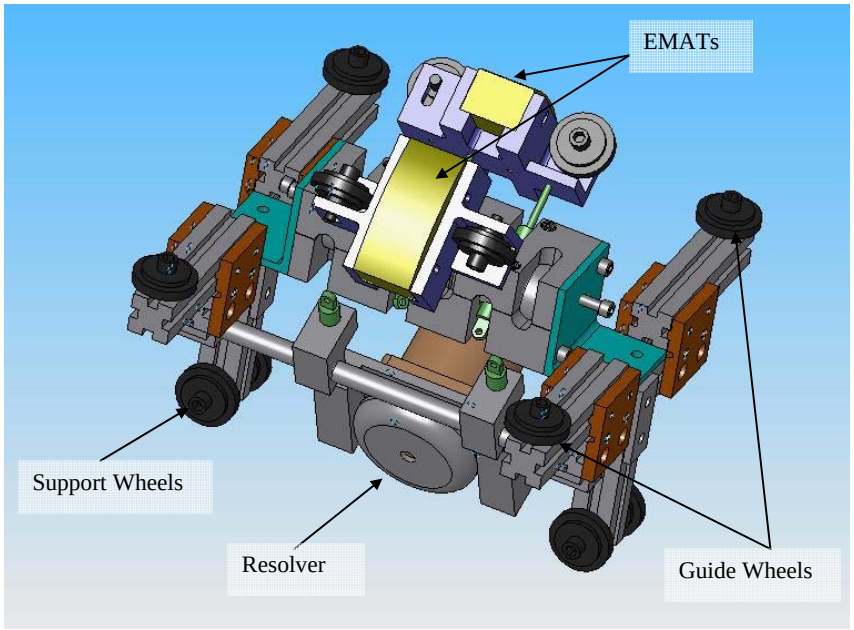


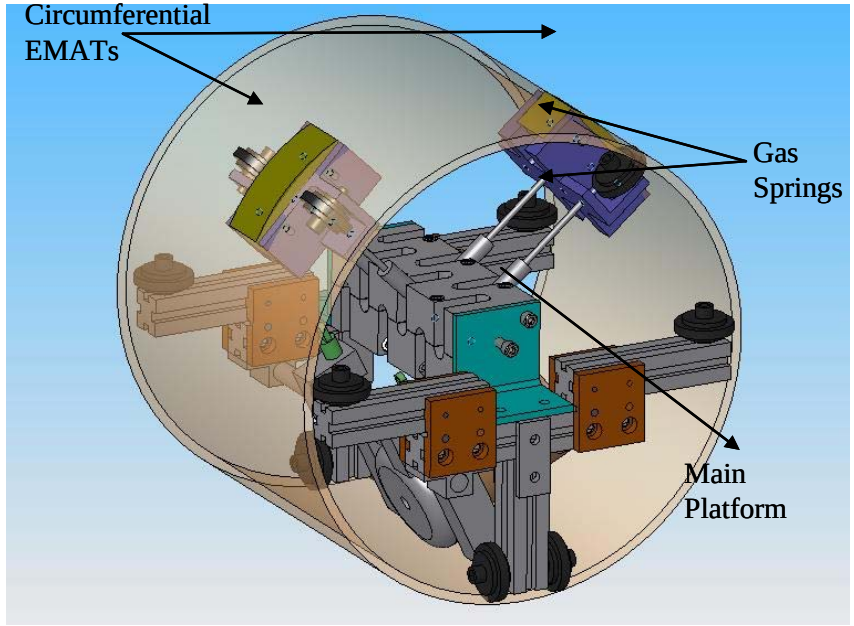


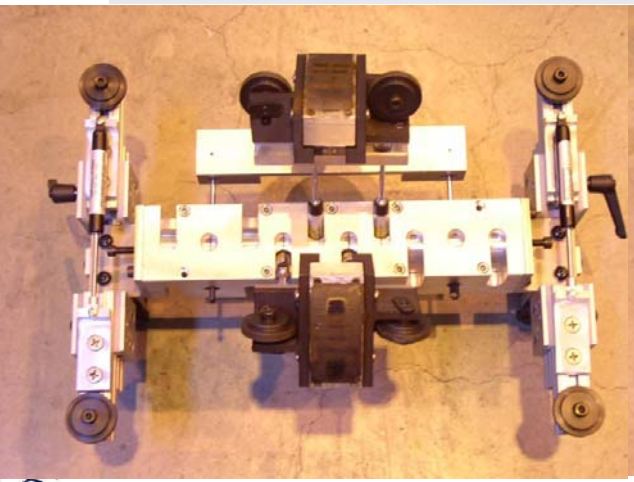
Circumferential EMAT

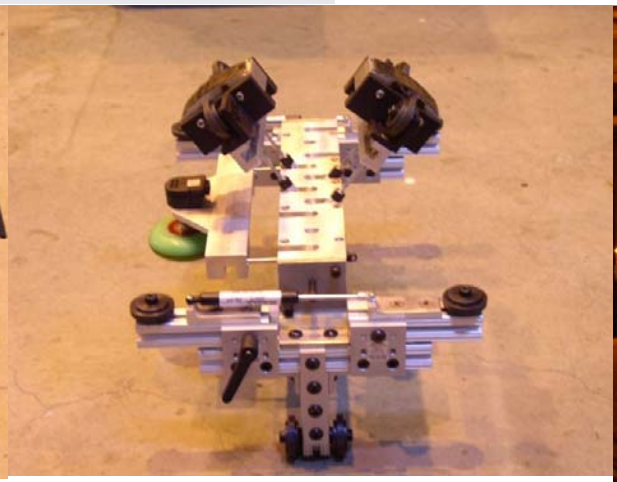
Axial EMAT

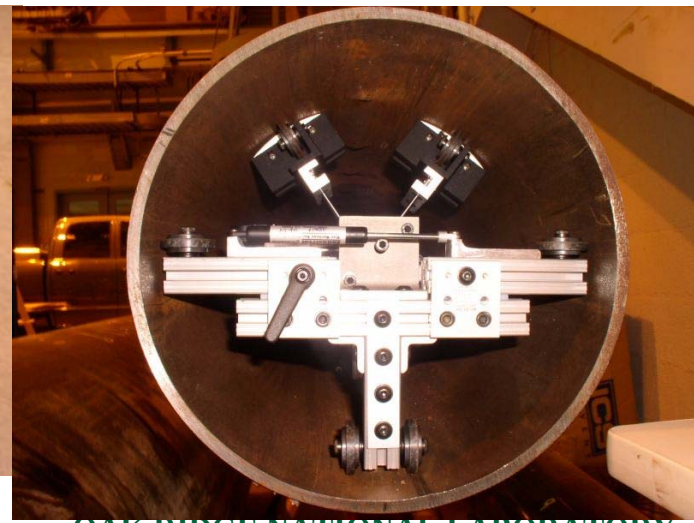
Mobile Platform Design











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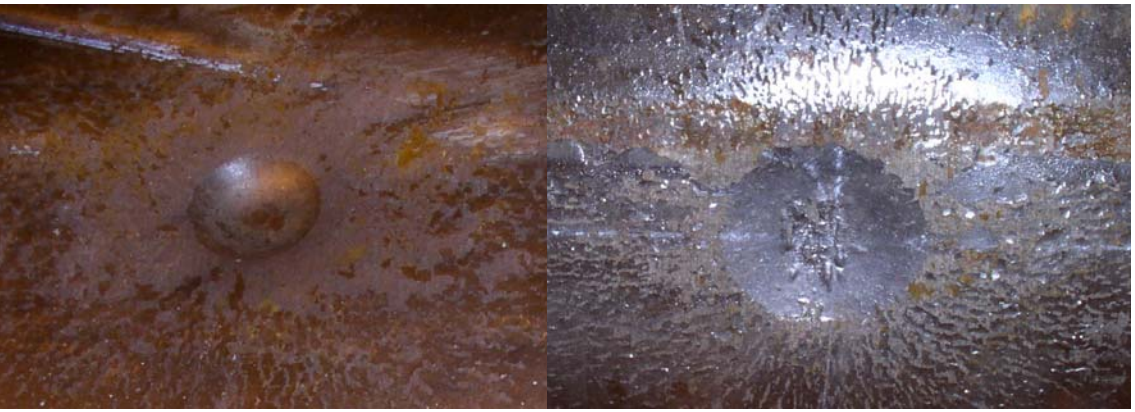
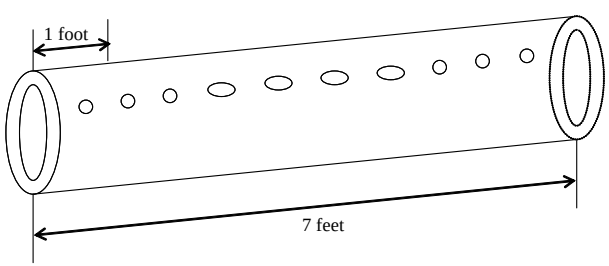
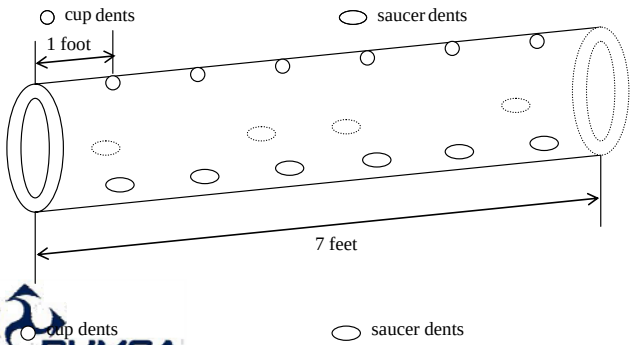
Specimens and Test Setup



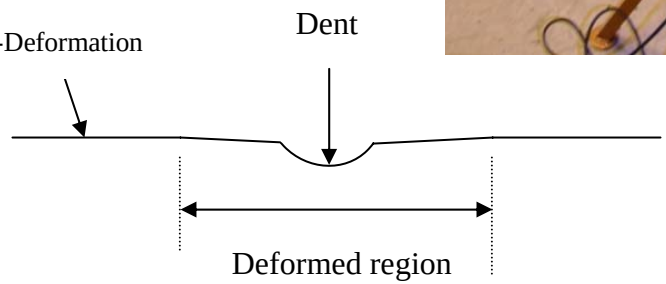
Cup and saucer on a 12-inch pipe



Pipe #1



Pipe #2



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Dent Description and Data Collection

Table 1 Dents description on pipe #1

Dent number, type and position (inch)	Diameter (inch)		Depth (inch)	Area of deformation	Ball Diameter (inch)
	Axial	Circumferential			
1 Cup (6.75)	0.59	0.59	0.238	1.8 x 1.3	1
2 Cup (14.9375)	0.65	0.65	0.345	3.5 x 2.2	
3 Cup (23.125)	0.63	0.63	0.318	2.5 x 1.6	
4 Saucer (31.3758)	1.185	1.02	0.305	3.2 x 2.2	3.75
5 Saucer (39.5625)	1.5	1.294	0.499	5 x 3.2	
6 Saucer (47.3125)	1.34	1.14	0.283	3 x 2	5
7 Saucer (55.25)	1.79	1.4	0.358	4.4 x 2.8	
8 Cup (63.375)	0.515	0.515	0.220	1.50x 1.3	0.75
9 Cup (71.375)	0.5	0.5	0.198	1.5 x 1.3	
10 Cup (79.4375)	0.546	0.54	0.249	1.8 x 1.5	

File Name	Begin position (from far end 'dent 10")	End position (dent 1 end)
Data 11	0	0.125"
Data 12	0	-0.125"
Data 13	0	0.0625"
Data 14	0	0.0625"
Data 15	0	0

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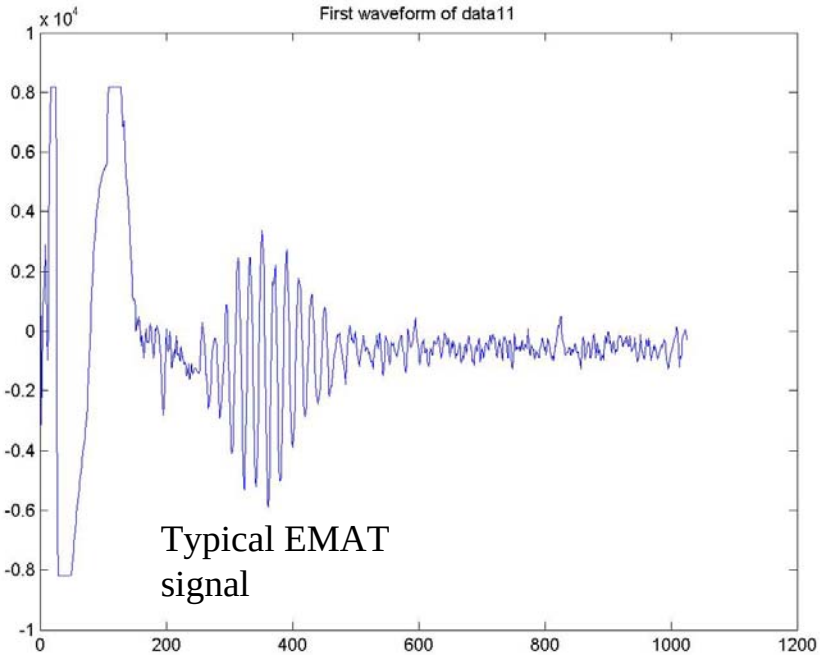
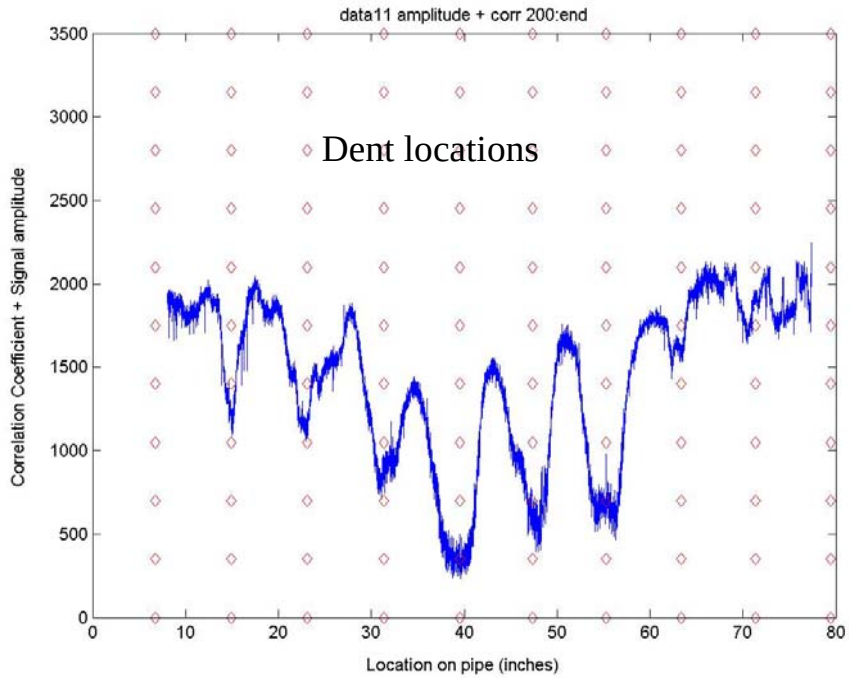
Dent detection and localization





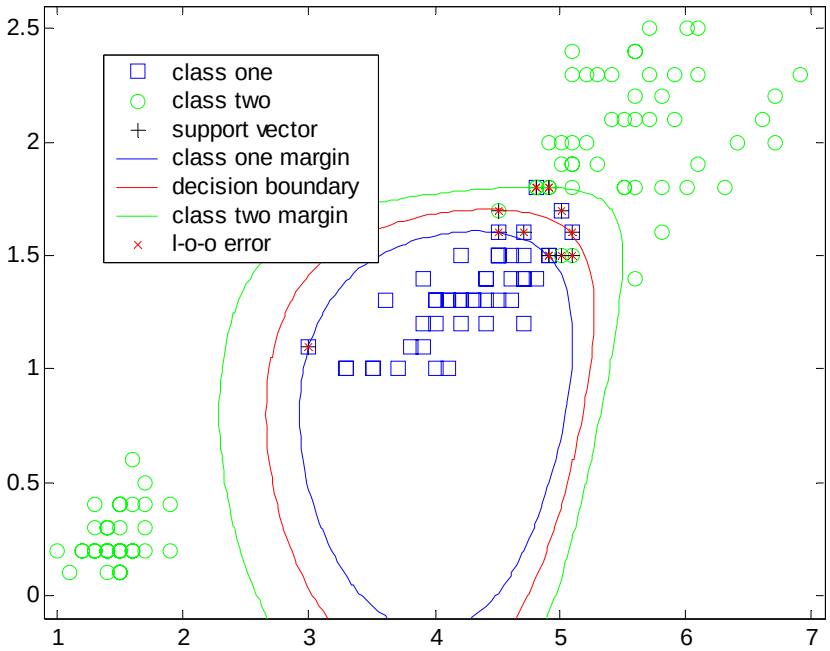
data11	*14.9750*	*22.9877*	*31.0676*	*39.5776*	*47.9265*	*55.8355*	*62.3054*	*70.4464*
data12	*15.1846*	*22.3126*	*30.8035*	*39.6489*	*49.6854*	*55.1963*	*62.3599*	*70.4044*
data13	*14.9432*	*22.4887*	*30.7458*	*39.4991*	*47.0139*	*55.4314*	*62.4274*	*71.5027*
data14	*15.1662*	*23.0520*	*31.0616*	*39.7834*	*47.2249*	*55.2507*	*62.4129*	*71.4836*
data15	*15.2893*	*22.7862*	*31.8016*	*40.5033*	*48.2634*	*55.1873*	*63.1101*	*70.5199*

True location	*14.9375*	*23.125*	*31.3758*	*39.5625*	*47.3125*	*55.25*	*63.375*	*71.375*

Dent Classification

Support Vector Machine (SVM) Classifier

The geometrical interpretation of SVM is searching for the optimal separating surface, i.e. the hyper-plane that is, in a sense, equidistant from the two classes.

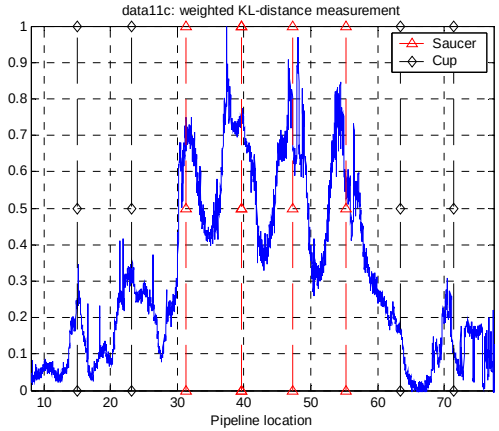


Example of applying SVM to separate two classes of data

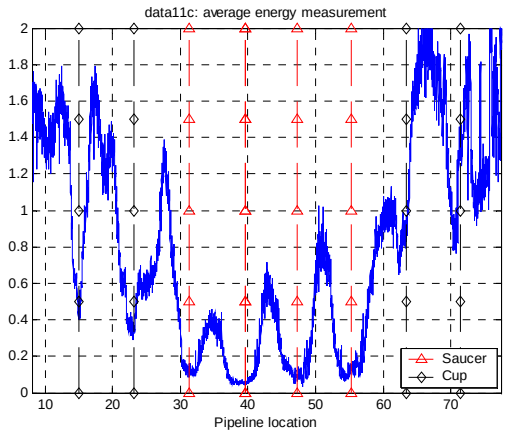
Feature Extraction

- *Relative Entropy Measurement*

  Kullback Leibler distance (KL-distance)



- *Average Energy Measurement*



- *Frequency Spectrum Density Shift*

Dent Classification (cont'd)

- Based on the dent information, we define five classes such that
  - "1": normal condition
  - "2": cup deformed region
  - "3": cup dent
  - "4": saucer deformed region
  - "5": saucer dent

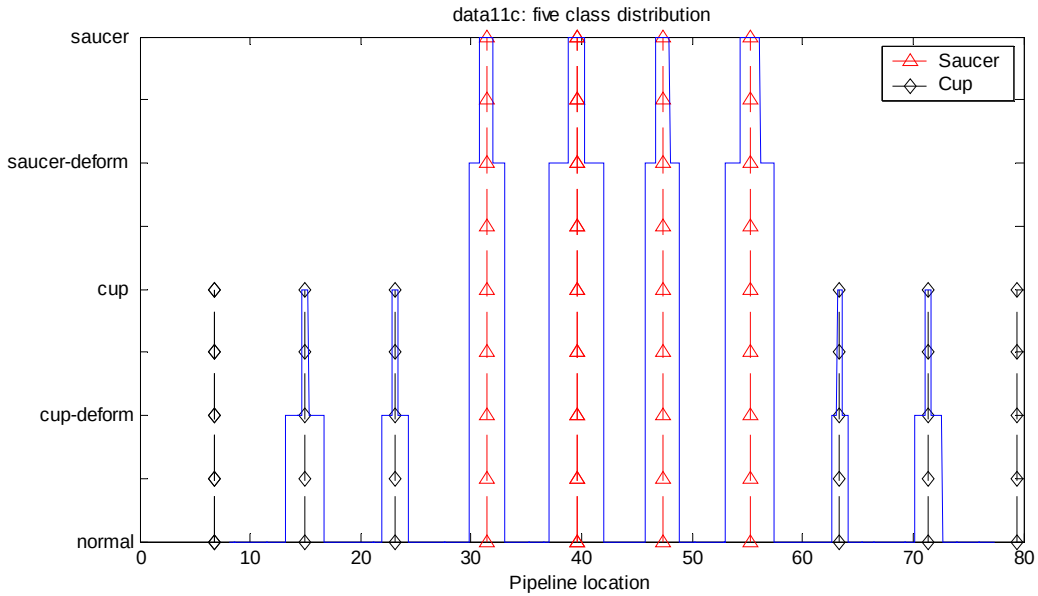


Table 2 SVM Leave-one-out Classification Results

		Leave-one-out training/testing (each item below is leaved out separately)							
		2-Cup	3-Cup	4-Saucer	5-Saucer	6-Saucer	7-Saucer	8-Cup	9-Cup
Dent region	trained data	95.12	95.32	95.36	95.36	95.29	95.30	96.59	98.89
	leaved data	100	82.76	100	100	100	91.99	79.45	65.99

Dent Classification (cont'd)

Comparison with PCA-DA based classification method.

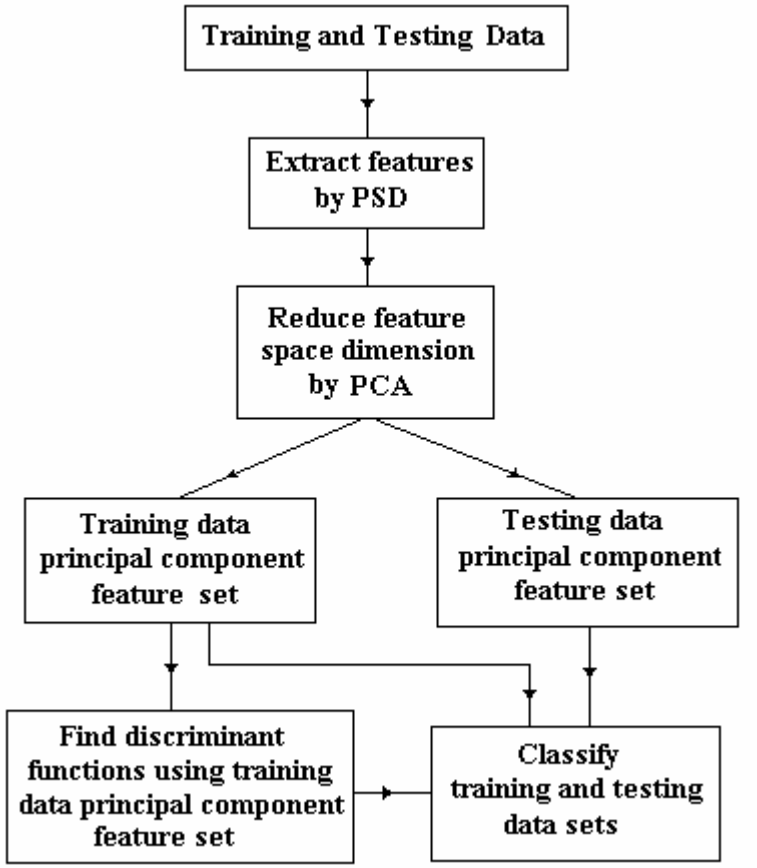


Table 3 Dent classification in pipe #1 with PCA-DA

Data11	Number of samples	Labeled as Cup	Labeled as Saucer	Accuracy
Cup	16	14	2	88%
Saucer	16	0	16	100%

Data12	Number of samples	Labeled as Cup	Labeled as Saucer	Accuracy
Cup	16	13	3	81%
Saucer	16	4	12	75%

Data13	Number of samples	Labeled as Cup	Labeled as Saucer	Accuracy
Cup	16	16	0	100%
Saucer	16	4	12	75%

Data14	Number of samples	Labeled as Cup	Labeled as Saucer	Accuracy
Cup	16	16	0	100%
Saucer	16	4	12	75%

Data15	Number of samples	Labeled as Cup	Labeled as Saucer	Accuracy
Cup	16	14	2	88%
Saucer	16	2	14	88%

Accomplishments and Conclusions

- We were able to model the 3-D dents wave scattering problem through an extensive boundary element analysis approach. The scattering pattern with respect to dent shape, size, and frequency response could be further studied. However, it requires some extensive mesh generations and our BEM code may still have bugs that need to be fixed.
- We have successfully developed a mobile EMAT fixture that can accommodate 8”~12” pipes and carry both circumferential and axial EMAT probes inside the pipe. The fixture has gas springs for loading the EMAT against the pipe wall and has a potentiometer encoder to record the positions so that the defects can be localized
- Extensive SH EMAT data were collected when the platform goes through two 12” diameter seamless pipes with both “Cup” and “Saucer” shaped dents. Data preprocessing was performed to eliminate the bad data due to DAQ synchronization problem and EMAT glitches. All the dents that are deformed 25% of wall thickness are successfully detected and localized. The location error of the dents is within 1”
- Several data features and pattern classifiers were evaluated to detect and classify the dents. For example, when signal energy, the power density spectrum, and the *Kullback Leibler* distance (KL-distance) were used as features, a support vector machine classifier can achieve above 90% of correct rate for “cup” and “Saucer” dents. Our previous developed PCA-DA approach was also tested with comparable performance.

Future directions

- Mechanical dents inspection with coating
- Coating delamination inspection
- 3-D BEM modeling effort
- Defect size and shape estimation
- Magnetostrictive EMAT sensor design
- Integration with CMU and Foster Miller platforms
- Field demo and beyond

- - - What is PHMSA's vision/priorities in the future R&D?

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