LM027- Enhanced Resonance Inspection for Light Metal Castings

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Presentation Outline

- Ultimate goals and relevance
- Project timeline, budget and status
- Background
- Technical gap and technical approach
- Technical accomplishments
- Summary and future work
- Project participants
- Publications

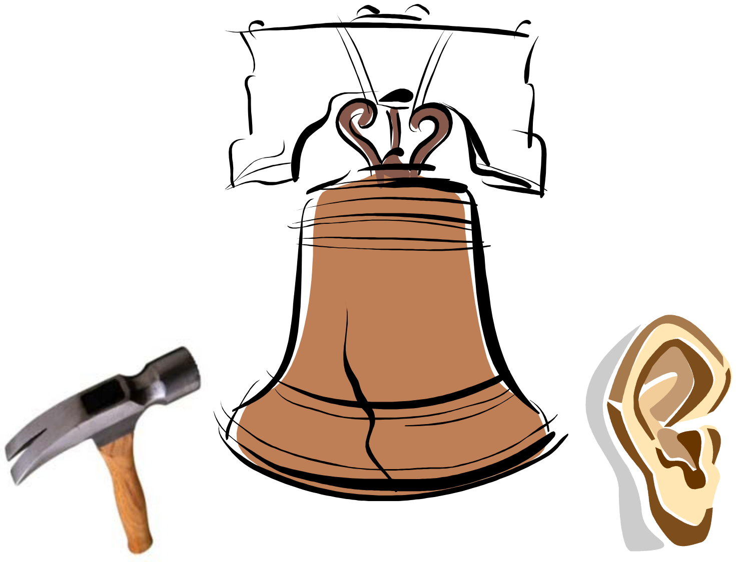
Ultimate Goals – Lightweight Materials Goals

- Validate the *cost-effective* reduction of the weight of passenger vehicle body and chassis systems by 50 percent with *safety*, performance, and recyclability comparable to 2002 vehicles;
- Exhibit *performance*, *reliability*, and *safety* characteristics comparable to those of conventional vehicle materials;
- Enable development and commercial availability of low cost magnesium and its alloys, low cost carbon fiber and its composites, other *light metal alloys*, and next generation high-strength steels, with lifecycle costs equivalent to conventional steel.

Objectives and Status of the Two Projects

- *Concept feasibility* of *computationally enhanced* resonance inspection for light metal castings.
- 2.25-year project
- Total project budget: $568.7K ($365.2k cash, $203.5k in-kind)
- $340K total funding to PNNL for computational work:
  - FY07-FY08: USAMP
  - FY09: direct funding
- Status:
  - Successfully demonstrated that computational tools can be used to enhance resonance inspection.
  - Technical feasibility study under way in USAMP NDE 901.

Basic Concept of Resonance Inspection



Excitation
Instrumented hammer
Piezo – scanned
Piezo – chirped
…

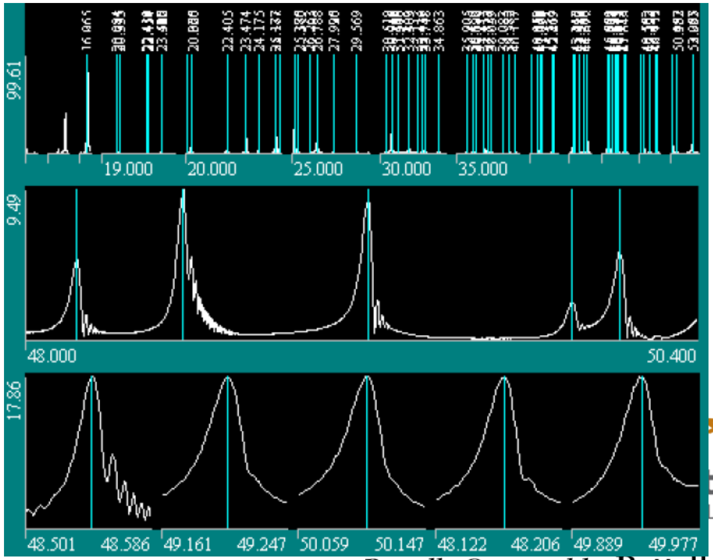
Detection
Microphone
Piezo-contact
Laser deflection
…

Advantages

- Handles complicated geometries
- Fast (1 sec/part)
- Inexpensive
- Multiple vendors
- Robust, process-compensated sorting algorithms used in production

Today’s Resonance Inspection in Production

- ☐ Emerging NDE technology for castings, forgings and PM parts
- ☐ Sensitive to mechanical variations – holds potential to ascertain structural integrity with high accuracy, low cost and high speed
- ☐ Does an empirical sort
- ☐ Relies on detecting the natural resonance frequencies of a part
- ☐ Currently used by several automotive suppliers of aluminum castings for performance and safety critical applications



Technology Gaps

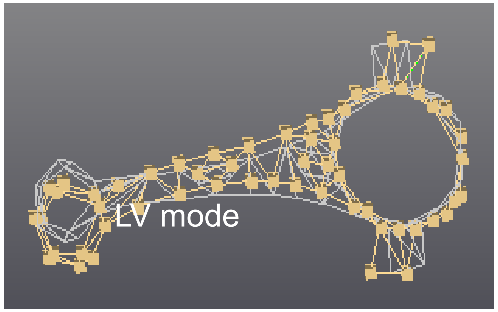
- Sort algorithms based on training sets of good & bad parts:
  - Large amount of parts required for training sets – Time consuming;
  - No clear criterion for sufficient training
- Small processing changes may ruin the sorting rules
- Unknown sensitivities to specific defects
  - Degree of confidence
- Can not pin point defect location, size and type
  - Contrast with conventional NDE
  - Conceptual hurdle

Technical Approach Used to Overcome Technology Gaps

- Develop a set of *validated* computational tools to enable predictive capabilities for enhanced resonance inspection:
  - Finite element-based modal analysis to translate materials properties and geometry into predicted frequencies and mode shapes;
  - Computational methods to identify mode shapes for each frequency measured;
  - Computational methods to provide sensitivity analysis to critical anomalies;
  - Computational method to pinpoint possible flaw location.

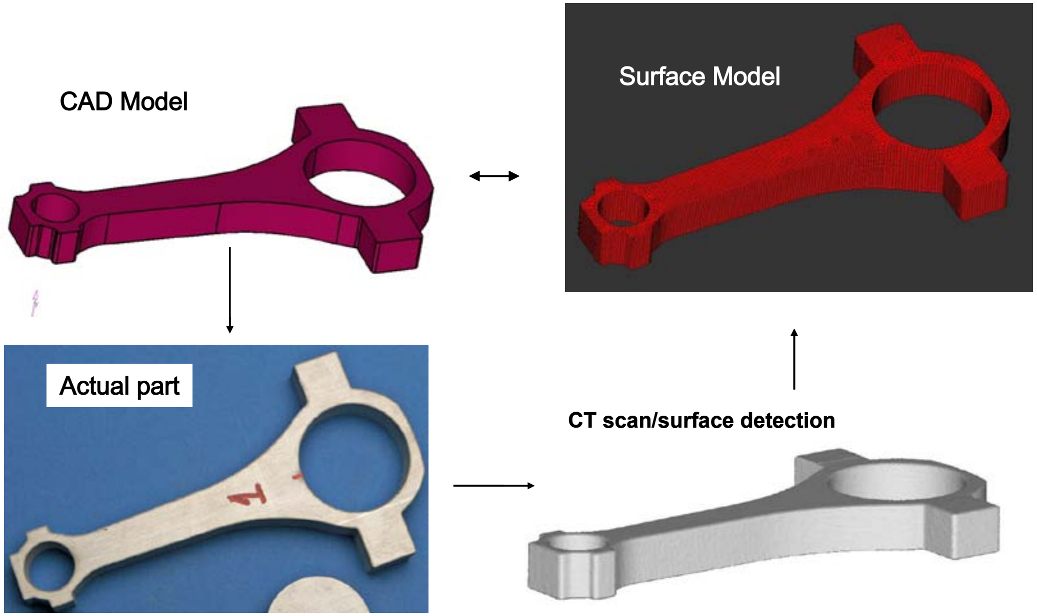
Plans to Overcome Technical Challenges

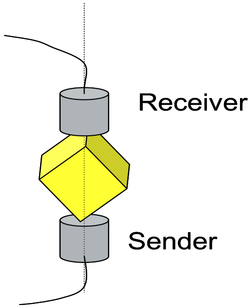
Risk/challenge	Plan to overcome challenge	Explanation
Prediction accuracy for mode frequencies may be limited by computational state-of-the-art	Document, then transfer emphasis to prediction of frequency shifts	Frequency shifts are the most important component in present sorting algorithms
Prediction accuracy for mode frequencies may be limited by materials inhomogeneity	Determine variations in density and moduli from experiments or casting codes	Property variations can be mapped by computed tomography or other techniques
High mode density may confound identification of mode shapes	Supplement computations with laser vibrometry or other experimental approach	Direct measurement of mode shapes is possible and can be used to identify exact shapes



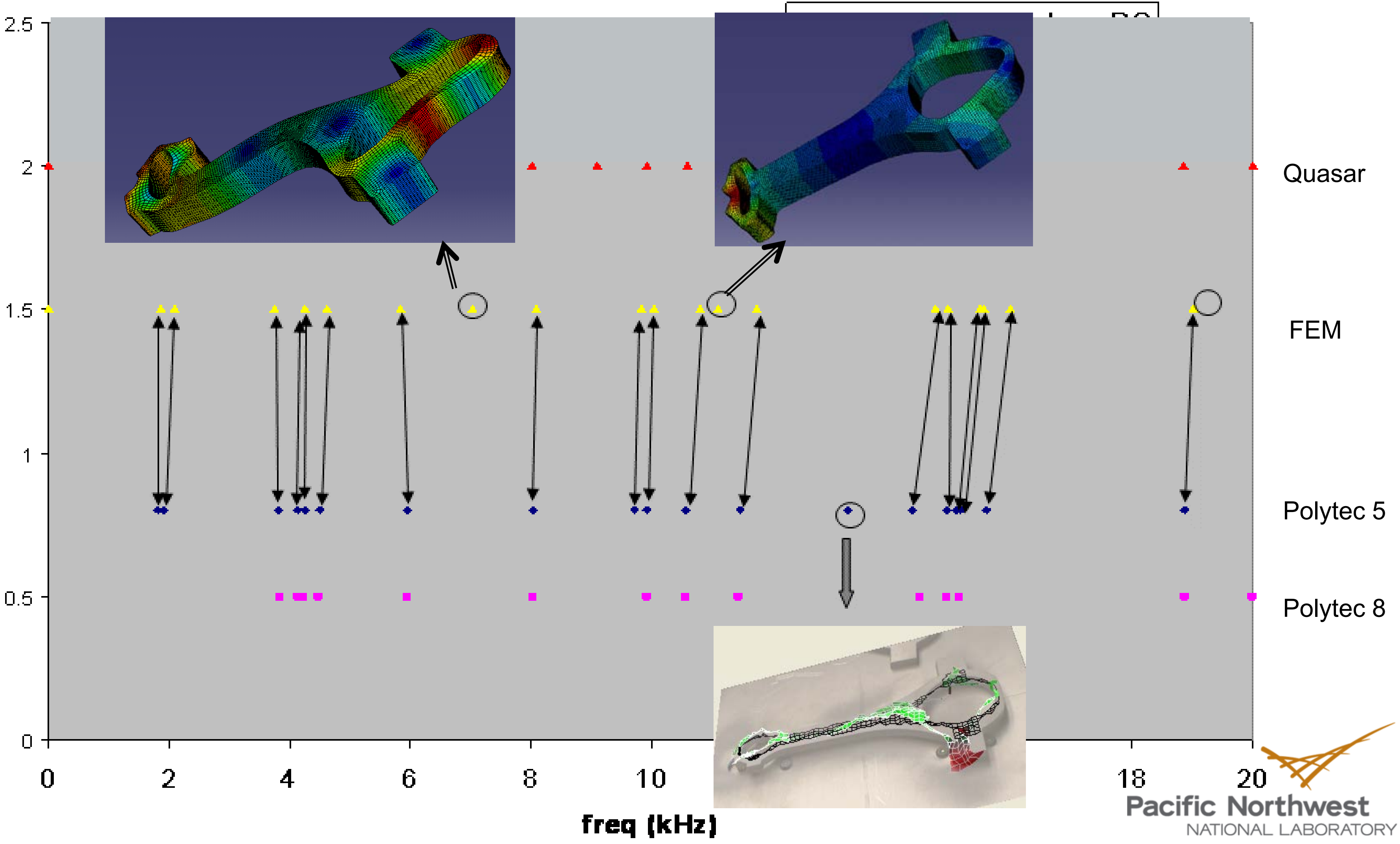
Development of Finite Element-Based Modal Analyses Procedures - Simple Connecting Rod

- Finite element modal analysis based on actual scanned geometry and measured properties:
    - Geometry: CT scans at 160 kV with 0.5 mm resolution
    - Meshing of actual scanned geometry
    - Material properties measured using resonance spectroscopy
- Finite element model
    - Mesh size sensitivity studies completed: 1mm mesh sufficient
    - Free boundary conditions applied
    - Frequency extraction performed





Model Validation and Verification with Connecting Rod



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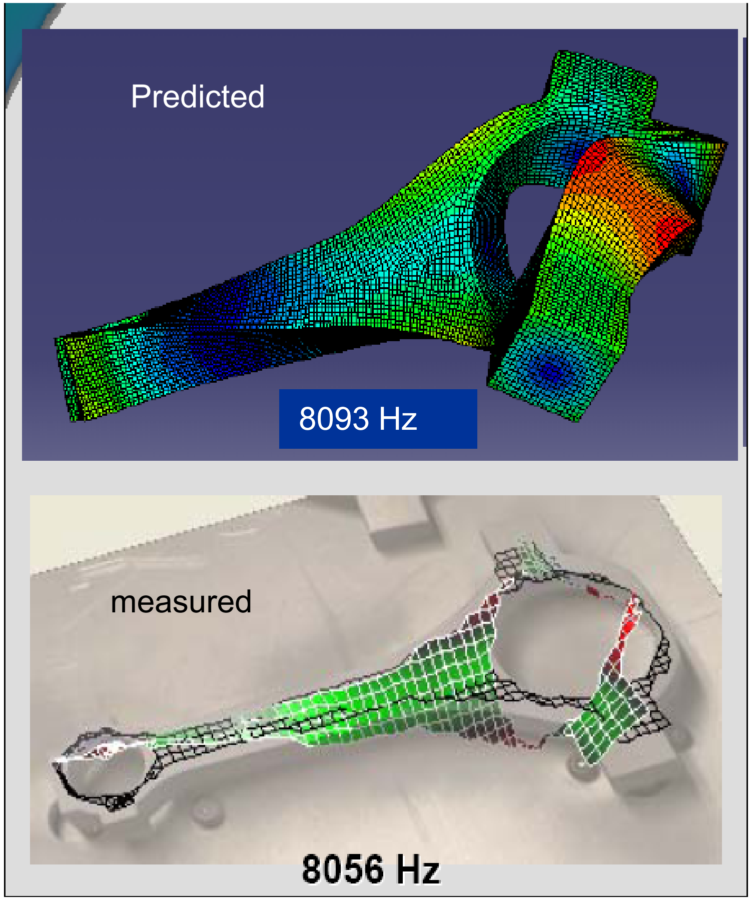
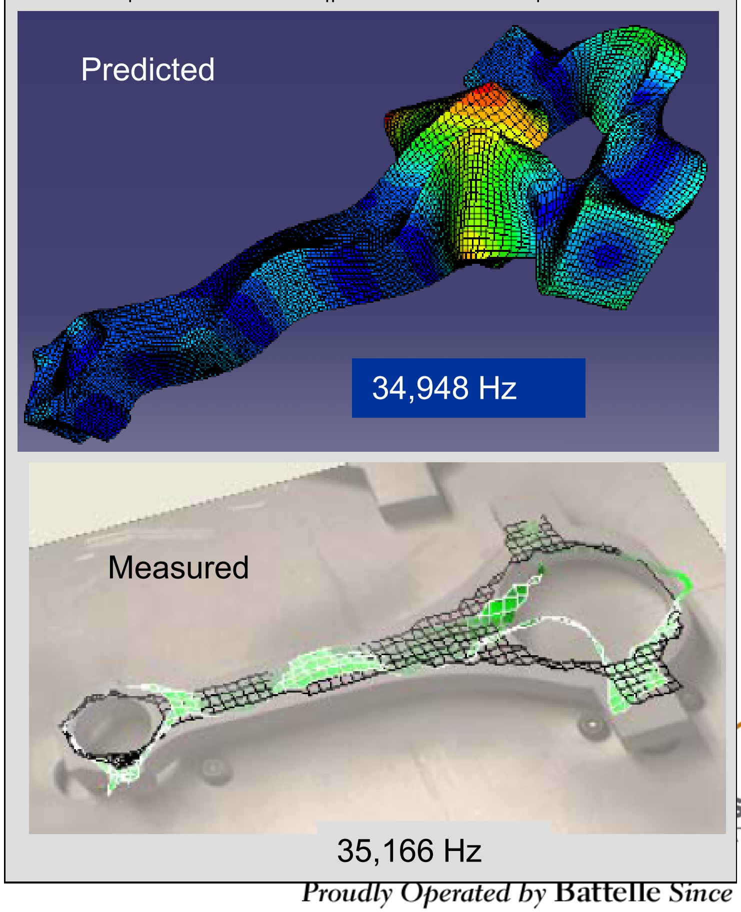
Development of Computational Tools for Enhance RI

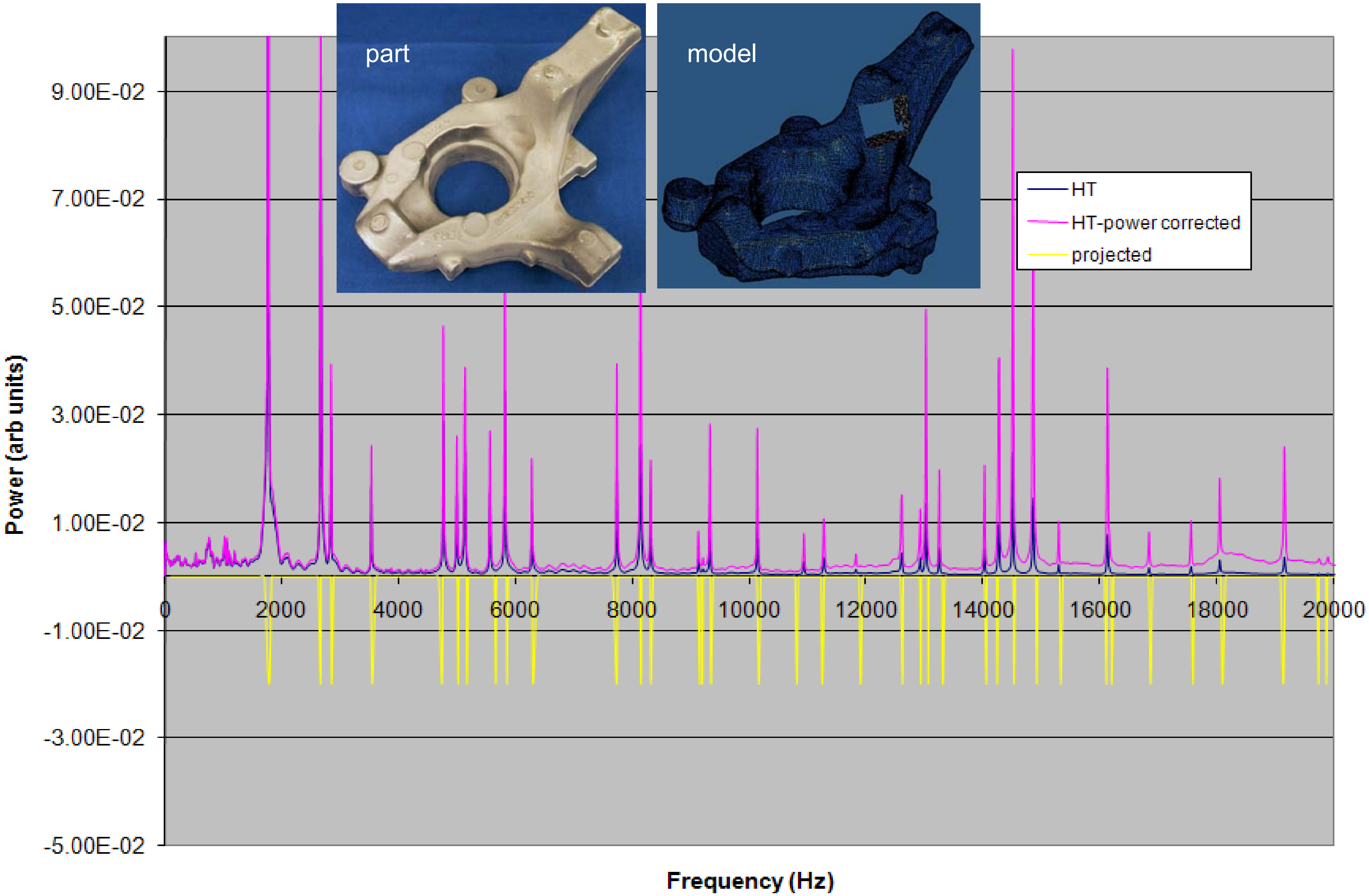
Developed and implemented algorithm for automatic mode matching between measured and predicted mode shapes:

$$\frac{\left|\int_S u_L^* \bullet u_F \, d\sigma\right|^2}{\left|\int_S u_L^* \bullet u_L \, d\sigma\right|\left|\int_S u_F^* \bullet u_F \, d\sigma\right|}$$

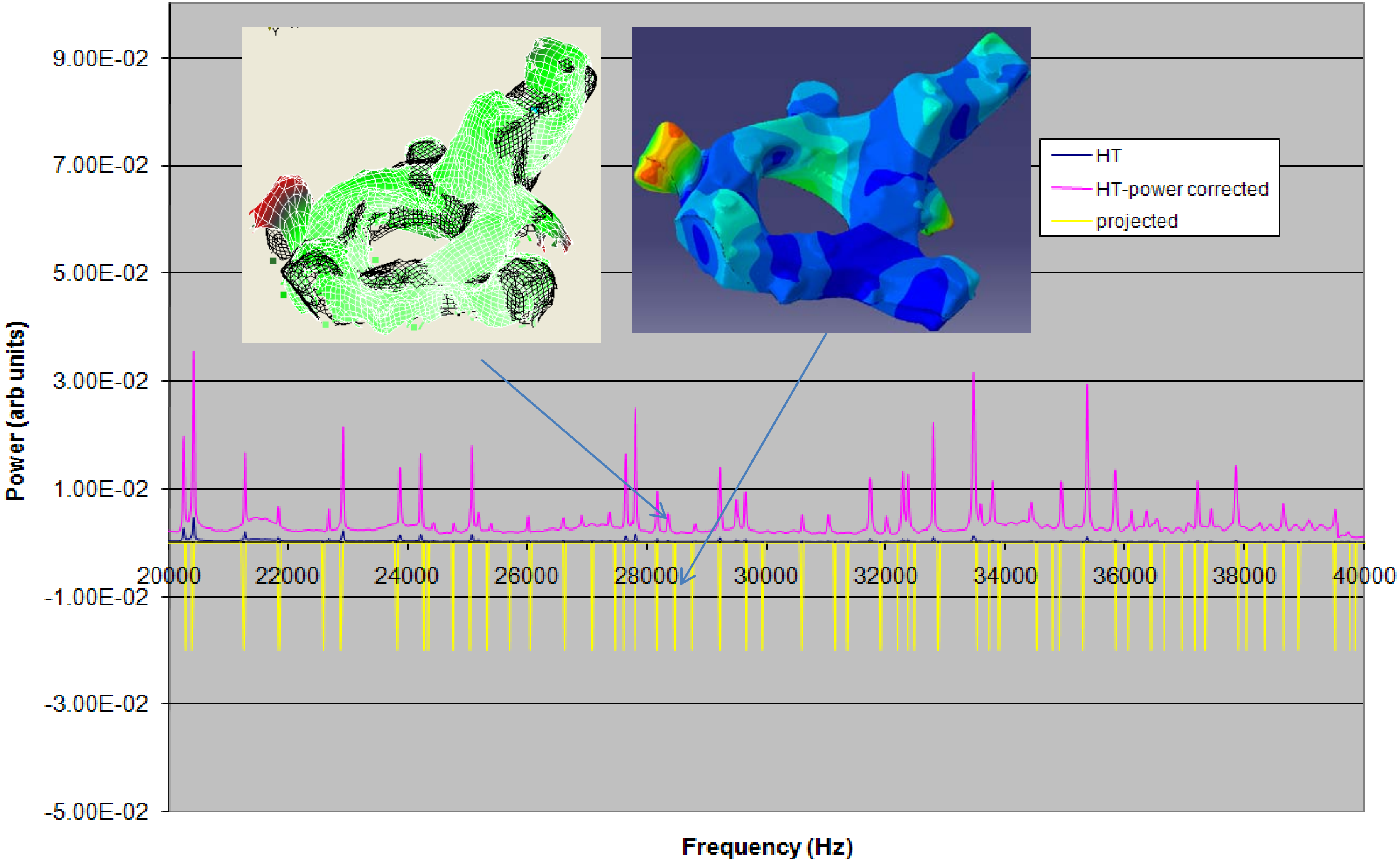




Validation and Verification of Finite Element-Based Modal Analyses on Production Level Part – Accuracy Achieved

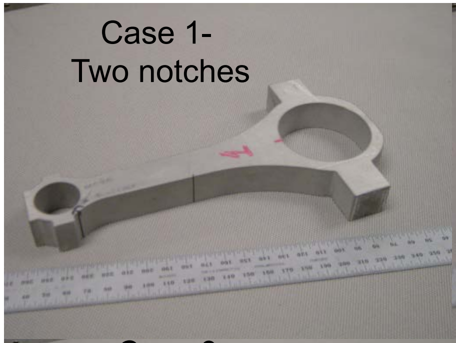


Higher Frequency Range Correlation



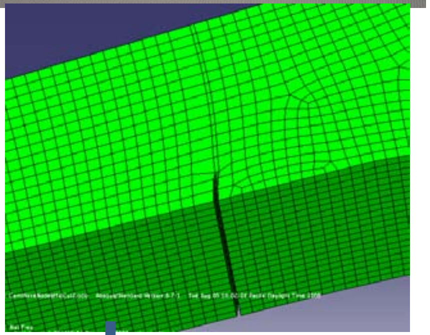
Quantify Flaw Sensitivity with Controlled Flaws

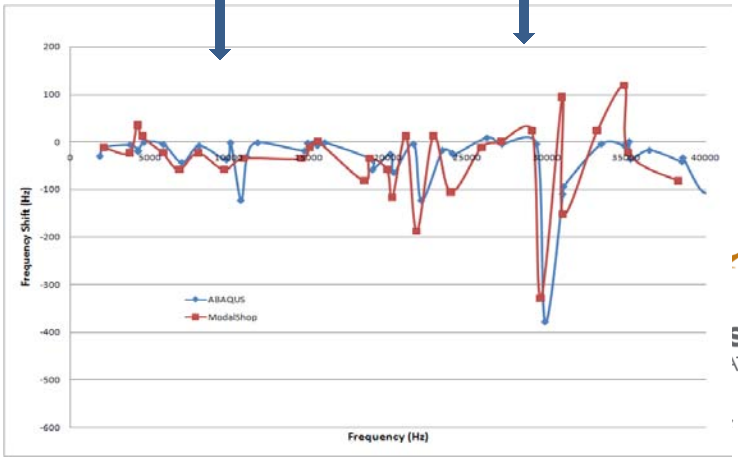
- Part fabrication
  - EDM notches at three different locations
- RI measurements
  - Quasar
  - The Modal Shop
- Finite element modeling – time consuming
- Analytical perturbation analyses – Very fast, analytical based
- Frequency shift comparisons:
  - Experimental measurement
  - ABAQUS simulation
  - Perturbation results


Case 1-
Two notches


Case 2-
Big end notch


Case 3-
Mid-shank notch

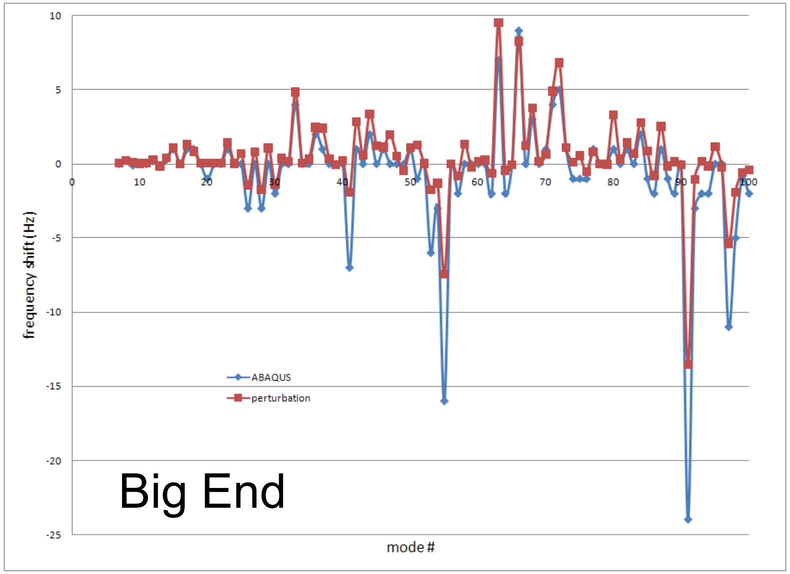


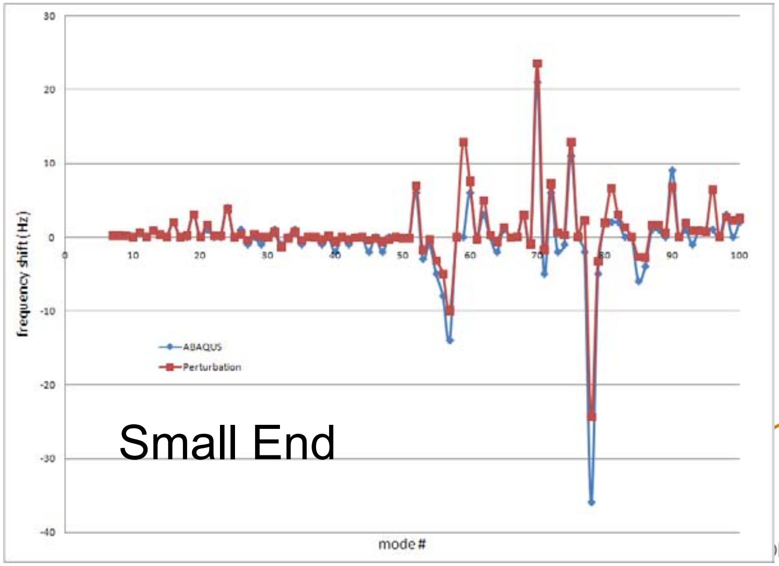


Developed Analytical Perturbation Analysis to Predict Frequency Shift Induced by Flaws

Frequency shift induced by small discrepancies in the part: stiffness sensitivity, density sensitivity and surface integral.

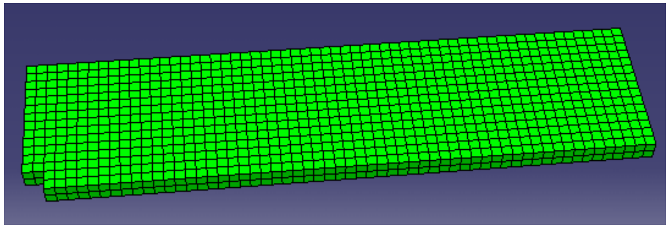
$$\frac{\Delta f}{f}=\frac{1}{2}\frac{\int \frac{\partial u_i}{\partial x_j}\Delta C_{ijkl}\frac{\partial u_k}{\partial x_l}dV}{\int \frac{\partial u_i}{\partial x_j}C_{ijkl}\frac{\partial u_k}{\partial x_l}dV}-\frac{1}{2}\frac{\int \Delta\rho u_i u_i dV}{\int \rho u_i u_i dV}-\frac{1}{2}\frac{\int_A n_j u_i c_{ijkl}\frac{\partial u_k}{\partial x_l}d\sigma}{\int \frac{\partial u_i}{\partial x_j}c_{ijkl}\frac{\partial u_k}{\partial x_l}dV}$$

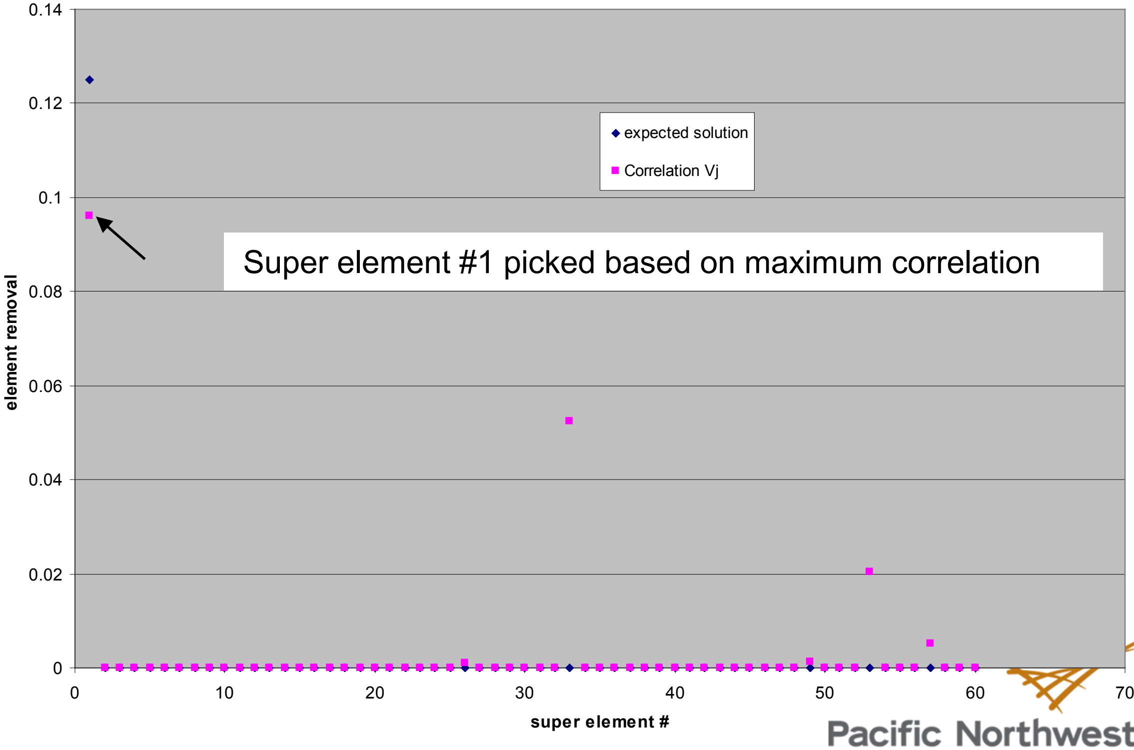




Algorithm Development for Identifying Possible Flaw Locations – Resonance Inversion

- Proposed method:
  - Divide a part into numbers of voxels
  - Predict the frequency shift by deleting each voxel
  - When given a frequency shift pattern, use maximum correlation to determine the size and location of each flaw
- Assumptions
  - Small flaw
  - Linear superposition of frequency shifts
- Preliminary results: Maximum correlation is able to pin point the flaw to the 1st super element





Super element #1 picked based on maximum correlation

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Conclusions and Future Work

- Progress to date has demonstrated concept feasibility of using computational tools to enhance RI techniques
  - Good resonance spectra comparisons between measurement and prediction have been obtained for both simple part and production part;
  - Methods and algorithms for mode shape correlation have been established;
  - Flaws in the form of crack and notch have been analyzed by both conventional finite element based analysis and linear perturbation analyses:
    - Linear perturbation shows promise for small, structural flaws
  - Preliminary results on resonance inversion by maximum correlation show promise
- Follow on work underway in NDE901

Project Participants

Automotive Participants

Ford Motor Company

Martin Jones

Jim Loeffler

General Motors

Cameron Dasch (Retired)

James Hetzner

Martin Kramer

Larry Ouimet

Dan Simon

Blair Carlson

Chrysler LLC

Randy Beals

Cliff Grupke

George Harmon

Industry Partners

Alcoa

Martin Brady

James Waters

Citation

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The Modal Shop

William Pohl

Gail Stultz

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