Early Fatigue Detection and Adaptive Life Management

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Waltham, MA

Navy Opportunity Forum, June 2013

MWM sensors and MWM-Arrays are covered by issued and pending patents, including, but not limited to: 8,237,433, 8,222,897, 8,050,883, 7,994,781, 7,876,094, 7,812,601, 7,696,746, 7,589,526, 7,533,575, 7,528,998, 7,526,964, 7,518,360, 7,467,057, 7,451,657, 7,451,639, 7,411,390, 7,385,392, 7,348,771, 7,289,913, 7,280,940, 7,230,421, 7,188,532, 7,183,764, 7,161,351, 7,161,350, 7,166,055, 7,095,224, 7,049,811, 6,995,557, 6,992,482, 6,952,095, 6,798,198, 6,784,882, 6,781,387, 6,727,691, 6,657,429, 6,486,673, 6,433,542, 6,420,867, 6,377,039, 6,351,120, 6,348,011, 6,198,279, 6,188,218, 6,156,330, 5,966,011, 5,792,086, 5,629,621, 5,990,677 and RE39,206 (other US/foreign patents issued and pending).

JENTEK Sensors, Inc.

- 20 year old company, 30+ people, 10 PhD’s
- Profitable business & growing market opportunities
- Strong Engineering-Science Team
- Extensive IP – over 50 Patents Issued
- Focus on sale of products to meet key customer needs
  - Aerospace & Defense business is growing
  - Oil & Gas business is growing fast

**JENTEK’s Digital Eddy Current product line is a **U.S. Navy Standard Practice**, and “**technical aspects are FAA approved**” for some commercial applications."
Production / Inspection Systems in Use

Military
- NAVAIR FRC-E use since April 2005
  - Detected large and small cracks **not detected** by conventional Eddy Current Testing (ET) and Liquid penetrant testing (LPT)
  - Low False Indication Rate, high up-time, very competitive cost

Disk Slots

Blade Dovetails

Commercial
- In use for 1000s of commercial engine inspections, “Technical Aspects FAA approved”

**“Technical aspects of the method are FAA approved.”**

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MWM-Array & GridStation Products Provide High Return on Investment, Improved Safety

1992: JENETEK Founded by Dr. Neil Goldfine

2000: IN7000 Series Product Launch

2004: ASTM Standard E2338-04

2003: ASNT Materials Evaluation Best Paper Award

2004: Outstanding Phase III Transition Award, Awarded by the Navy Transition Assistance Program

2006: National Tibbetts Award

2008: FAA/ATA Engine Component Inspection Technology

2012: 8200 Series Product Launch

2013: $10M of IN7000 Product Sold

> $100M Customer ROI

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Problem: Life Management of Dynamic Components

- **Rapid and Uncertain** Damage Evolution
- Existing NDT and life management approaches not sufficient
- Non-relevant defects that do not grow into fatigue cracks confuse available inspection methods
- **No framework** exists for CBM+ decision support, using advanced NDT data

**Solution:** *MWM-Array Mapping & Tracking and Component Adaptive Life Management Software (CALM™) with early damage detection*
## CALM™ for Rotorcraft Dynamic Components and Engine Components with NDT Mapping & Tracking

<table>
<thead>
<tr>
<th>Features</th>
<th>Advantages</th>
<th>Benefits</th>
</tr>
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<tbody>
<tr>
<td><strong>Fuzzy HyperLattices for rapid risk assessment</strong></td>
<td>• RUL predictions with confidence intervals&lt;br&gt;• Predicts risk of failure before next inspection in real time on NDT platform&lt;br&gt;• RUL incorporates inspection uncertainties and historical/current inspection results</td>
<td>• Immediate feedback to inspector&lt;br&gt;• Immediate scheduling of next inspection based on risk&lt;br&gt;• More accurate RUL predictions enables more cost-effective maintenance&lt;br&gt;• Improved safety margins and readiness</td>
</tr>
<tr>
<td><strong>Early Damage Mapping &amp; Tracking using MWM-Array</strong></td>
<td>• Detects damage prior to rapid growth&lt;br&gt;• Tracks damage growth for historical failure analysis and for RUL/ failure risk prediction&lt;br&gt;• Reliable high resolution images of early fatigue damage with evolution tracking</td>
<td>• Enables damage growth rate computations with confidence intervals&lt;br&gt;• High repeatability&lt;br&gt;• More accurate RUL predictions enables more cost-effective maintenance&lt;br&gt;• Improved safety margins and readiness&lt;br&gt;<strong>Proven NDT method, now in-use</strong></td>
</tr>
<tr>
<td><strong>Fleet-wide statistics recording and individual component tracking</strong></td>
<td>• Reliable/repeatable data for all metals&lt;br&gt;• Digital archiving and real-time updating captures damage growth statistics for populations and subpopulations of components across the fleet</td>
<td>• Improves fleet condition knowledge / enables improved maintenance planning&lt;br&gt;• Life extension through early damage detection and prompting CBM actions (e.g. repairs and surface treatments) – <strong>cost reduction</strong>&lt;br&gt;• Improved safety margins and readiness</td>
</tr>
<tr>
<td><strong>Probability of Detection (POD) verification and real-time updating of inspection confidence intervals</strong></td>
<td>• Verification of inspection performance&lt;br&gt;• Real-time verification that POD curve assumptions are still correct for each inspected feature</td>
<td>• Substantially improved inspection reliability, improving safety&lt;br&gt;• POD verification enables RUL estimation and risk assessment&lt;br&gt;<strong>Other NDT methods can’t provide this</strong></td>
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## MWM-Array Damage Mapping & Tracking for CALM

<table>
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<tr>
<th>Features</th>
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</tr>
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<tbody>
<tr>
<td><strong>MWM-Array sensor</strong>&lt;br&gt;Flexible linear-drive eddy current array</td>
<td>• Rapid scanning/inspection of wide areas and complex features&lt;br&gt;• Dramatically outperforms conventional and other advanced eddy current testing (ET) methods</td>
<td>• Technical aspects FAA approved for some commercial engine inspections&lt;br&gt;• Current US NAVY standard practice&lt;br&gt;• Faster, more accurate, more cost-effective maintenance</td>
</tr>
<tr>
<td><strong>GridStation parallel architecture instruments</strong>&lt;br&gt;with new 8200 product launch, providing 18 to &gt;100 channels</td>
<td>• Many fully parallel channels with extremely high fidelity impedance data over a wide frequency range&lt;br&gt;• High quality impedance data</td>
<td>• Rapid inspection and rapid data acquisition, providing frequency data with for up to four frequencies simultaneously&lt;br&gt;• Suitable for model-based inverse methods <strong>No other systems provide this quality of data</strong></td>
</tr>
<tr>
<td><strong>Grids</strong> (2-unknowns), <strong>Lattices</strong> (3-unknowns) and <strong>HyperLattices</strong> with hierarchical inverse methods</td>
<td>• Rapid data analysis&lt;br&gt;• Extremely reliable inspections with real-time assessment of POD performance and verification of POD assumptions&lt;br&gt;• Real-time confidence interval calculations for NDT results</td>
<td>• Only ET method providing real-time feedback to operator on coverage and lift-off (proximity of sensor to surface) for each inspected location throughout inspection region&lt;br&gt;• Improved RUL and risk prediction estimates</td>
</tr>
<tr>
<td><strong>GridStation Software</strong> for data acquisition, visualization, archiving and decision support</td>
<td>• User friendly software interface&lt;br&gt;• Grid-based MWM-Array data visualization and high resolution imaging support&lt;br&gt;• Provides POD performance verification and statistics needed for RUL estimation and risk assessment</td>
<td>• Provides substantially improved inspection reliability, leading to improved safety and more cost-effective maintenance&lt;br&gt;• Reduces inspection burden&lt;br&gt;• <strong>Next generation software will be platform independent</strong></td>
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Component, Adaptive Life Management – CALM™

**CALM™ Services**

Providing a Framework to
- track digital inspection data
- record events (e.g. impact damage)
- assess risk of failure before next inspection

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**Diagram:***

- Inspection (quality NDT & baseline)
  - Threshold: \( \hat{a}_0 \)
  - Accept: \( \hat{a}_0 \) Baseline subtraction
  - Inspection (in-service NDT)
  - Accept: \( \hat{a}_1 \)
  - Reject: rework
  - Reject: accept

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Component, Adaptive Life Management Services

CALM™ Services

- **Coupon Study**
  - **Signature Library**
  - **Fracture Mechanics (Model-Based) Fuzzy HyperLattice**
  - **Rapid Uncertainty Estimator (t₁)** (using precomputed databases)

- **Set t₁**
  - **Inspection (quality NDT & baseline)**
    - **Uncertainty Assessment** • fatigue tests • metallurgy • Fracture mechanics
  - ** statistical analysis**

- **POD (ROC) Curve Generation**
  - **Crack Cluster Supervisor**
  - **Model Recalibrator (learning)**
  - **Fracture Mechanics (Model-Based) Fuzzy HyperLattice**
  - **Conditional Uncertainty Estimator**

- **Fuzzy HyperLattice**
  - **Rapid Uncertainty Estimator (t₂)** (using precomputed databases)

- **Fleet Experience** • NDT results • Failures • Expert Input

- **OEM Knowledge Component Study**
  - **Coupon Study Signature Library**

- **Rapid Uncertainty Estimator (t₁)** (using precomputed databases)

- **Inspection (in-service NDT)**
  - **Baseline subtraction**
  - **cdf(a)₁**

- **Rapid Uncertainty Estimator (t₂)** (using precomputed databases)
  - **cdf(a)₂**

- **fracture mechanics (Model-Based) Fuzzy HyperLattice**

- **Inspection (quality NDT & baseline)**
  - **threshold**
  - **accept**
  - **reject**

- **t₀**
  - **t₁**
  - **t₂**

- **Decision**
  - **rework**
  - **accept**

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Coupon Study and Signature Library Generation

**CALM™ Services**

**Coupon Study**

**Signature Library**

Fracture Mechanics (Model-Based) Fuzzy HyperLattice

Rapid Uncertainty Estimator ($t_1$) (using precomputed databases)

Set $t_1$

POD (ROC) Curve Generation

Crack Cluster Supervisor

Fleet Experience • NDT results • Failures • Expert Input

Model Recalibrator (learning)

Fracture Mechanics (Model-Based) Fuzzy HyperLattice

Rapid Uncertainty Estimator ($t_2$) (using precomputed databases)

**Inspection** (quality NDT & baseline)

$\hat{a}_0$ threshold

Accept

Inspection (in-service NDT)

$\hat{a}_1$

Baseline subtraction

$\hat{a}_0$

Reject

Set $t_2$

Rework

Accept

Reject

$\hat{a}_1$

$\hat{a}_0$

$\hat{a}_1$

$t_0$

$t_1$
Coupon Testing to Build NDT Performance Statistics

Fatigue coupon test specimens machined from component

Images © JENTEK Sensors, Inc. 2013

Mapping & Tracking Damage with Validation/Verification

Averaged and Baselined Scans of Coupon 2, Back

- 7.7 mils
- 14.6 mils
- 18.3 mils
- 21.8 mils
- 23.9 mils
- 25.4 mils
- 26.2 mils

X axis (in)

Averaged and Baselined Scans of Coupon 2 Front, Channel 3, MWM-Array FA43

- 7.7 mils
- 14.6 mils
- 18.3 mils
- 21.8 mils
- 23.9 mils
- 25.4 mils
- 26.2 mils

X axis (in)

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POD Curve Generation & Statistical Analysis

CALM™ Services

Inspection (quality NDT & baseline)

Rejected

Fast Uncertainty Estimator ($t_1$)

Using precomputed databases

Signature Library

Fracture Mechanics (Model-Based)
Fuzzy HyperLattice

OEM Knowledge
Component Study

Initial Assessment
- Fatigue tests
- Metallurgy
- Fracture mechanics

Uncertainty Assessment
- Usage
- Residual stress
- Etc.

Set $t_1$

Statistical Analysis

POD (ROC) Curve Generation

Validate Coupon Data

Rework
Accept

Decision

Set $t_2$

Inspection (in-service NDT)

Baseline subtraction

$\hat{a}_0$ threshold

Accept

Reject

$\hat{a}_0$

$\hat{a}_1$

â vs a Coupon Results for POD Curve Generation

Using Mil-Hdbk-1823 Methodology
Rapid Risk and Remaining Useful Life Assessment

CALM™ Services

Fracture Mechanics (Model-Based) Fuzzy HyperLattice

Rapid Uncertainty Estimator (t₁) (using precomputed databases)

Inspection (quality NDT & baseline)

Initial Assessment fatigue tests metallurgy Fracture mechanics

Uncertainty Assessment usage residual stress etc.

Set t₁

POD (ROC) Curve Generation

Crack Cluster Supervisor

Fleet Experience NDT results Failures Expert Input

Model Recalibrator (learning)

Fracture Mechanics (Model-Based) Fuzzy HyperLattice

Rapid Uncertainty Estimator (t₂) (using precomputed databases)

Statistical Analysis

Conditional Uncertainty Estimator

cdf(a)₁

cdf(a)₂

Fracture Mechanics (Model-Based)

Fuzzy HyperLattice

OEM Knowledge

Component Study

t₀

t₁

t₂

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CALM™ Services
Component Adaptive Life Management

- POD curve generation for NDT & embedded sensors
- Risk assessment & RUL estimation
- Fleet transition support
- After market decision support

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Rapid Risk Assessment from NDT Data

Component Adaptive Life Management (CALM) software

Cumulative probability distributions for crack size at Time $t_1$

Cumulative probability distributions for crack size at Time $t_2$

Cumulative probability distributions for cycles remaining to reach critical crack size (0.08 in.)

Images © JENTEK Sensors, Inc. 2013
CH-53E Component Inspection

- Representative of in-service damage evolution
- Test repeatability and reliability
- Combine with coupon data to produce POD curves

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## Development Milestones Completed

<table>
<thead>
<tr>
<th>Milestone</th>
<th>TRL</th>
<th>Risk</th>
<th>Measure of Success</th>
<th>TRL Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demonstrate reliable crack detection with MWM-Array on similar components (e.g., engine components)</td>
<td>9</td>
<td>Low</td>
<td>Federal Aviation Administration – Air Transport Association (FAA-ATA) Better Way Award: Fleet Readiness Center (FRC) standard practice</td>
<td>Jan 2008</td>
</tr>
<tr>
<td>Perform subcomponent demonstration</td>
<td>5</td>
<td>Moderate</td>
<td>Demonstrate improvement over conventional NDT</td>
<td>June 2009</td>
</tr>
<tr>
<td>Develop adaptive asset management approach</td>
<td>5</td>
<td>Moderate</td>
<td>Establish sufficient capability for target application</td>
<td>Oct. 2009</td>
</tr>
<tr>
<td>Adapt measurement and calibration methods for mapping &amp; tracking</td>
<td>7</td>
<td>Moderate</td>
<td>Crack detection performance on coupons</td>
<td>Oct. 2012</td>
</tr>
<tr>
<td>Perform component fatigue test for actual rotorcraft dynamic component</td>
<td>7</td>
<td>Moderate</td>
<td>Crack detection and CALM performance on component</td>
<td>Nov. 2012</td>
</tr>
</tbody>
</table>
Next Steps

- Transition to Fleet for Target Applications
  - Deliver Mapping & Tracking solution to FRC
  - Record data for two years
  - Apply CALM and initiate life extension in 3rd year

- Partner with OEMs and FRCs
  - Transition numerous targeted life extension solutions

- Broaden CALM Services
  - Fleet-wide data analysis & life management
  - Fleetwide CBM+ services

**CALM & MWM-Array**  
*Reduced total ownership costs, ... Improve readiness and safety*  
Provided by JENTEK Sensors
Partners Sought

- **Program Office Support**
  - Further technology development
  - T&E for first CALM™ application
  - Transition to FRC-E and Navy depots

- **Partnerships and Customers**
  - Rotorcraft Primes
    - Sikorsky, Boeing and others
  - Army
Questions?

Come see us at Booth # A-416

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