Current Methodology for
Dynamic Stress-Strain Prediction for
Structural Health Monitoring and
System Load Prediction

Peter Avitabile, Chris Niezrecki
Structural Dynamics and Acoustic Systems Lab
University of Massachusetts Lowell
**Current Methodology for Dynamic Response**

Critical assumption that the loads and boundary conditions for the model are known

Fluid structure interaction models help predict forces but have many unsubstantiated assumptions
Fundamental Change in Approach

Develop FEA model as usual

Measure response using full field approaches
- Pontos for discrete points
- Aramis for surface strain

Advantage

No assumption as to load or boundary conditions

Actual displacement directly obtained

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**Fundamental Change in Approach**

Operating (Real-time) displacements are expanded to the full set of analytical degrees of freedom in the finite element model using orthogonal shape based expansion functions.

Provides full field displacement solution

\[
[T_u] = [E_n][E_a]^g \\
[RTO_n] = [T][RTO_a]
\]
Theoretical Approach – Expansion Methodology

Full-set degrees of freedom obtained from

$$\{X_n\} = [T]\{X_a\}$$

Reduced system matrices can be written as

$$[M_a] = [T]^T[M_n][T] \quad [K_a] = [T]^T[K_n][T]$$

System Equivalent Reduction Expansion Process (SEREP) Transformation

$$[T_u] = [U_n][U_a]^g$$

Real time operating data expanded using

$$[ERTO_n] = [T][RTO_a]$$
Real Time Operating Expansion

Expansion process has been demonstrated for several structures such as
- Apache wing
- dryer panel

Some actual real time operating data expansion for panel structures

Measurement Points

Expansion Shape Points

Apache Helicopter Wing Missile Firing System

Whirlpool Dryer Panel Model Correlation

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Experimental Data - Whirlpool Dryer Base

- RTO Expanded from 31 'a' set to 310 'n' set with experimental modes

\[
[T_U] = [E_n][E_a] \quad [RTO_n] = [T][RTO_a]
\]
Experimental Data - Panel Structure

'a' set

Limited Measurement Points

\[
[T_U] = [E_n][E_a]
\]

\[
[RTO_n] = [T][RTO_a]
\]
Fundamental Change in Approach

Using the real time operating data, expansion of limited sets of data will be interjected back into the finite element model to predict full field dynamic stress-strain.
Generic Rib Stiffened Panel Structure

A generic model is studied to prove methodology

Mode 1: 12.7 Hz
Mode 2: 45 Hz
Mode 3: 71.2 Hz
Mode 4: 90.4 Hz

FFT of Output Response at one sensor location
Generic Structure Expansion Results

(a) Sensor Location
(b) Response Location

(c) 3 Modes
(d) 6 Modes

FEA - Expansion

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Dynamic stress prediction at various times during transient

\[ [T_U] = [E_n][E_a] \]

\[ [RTO_n] = [T][RTO_a] \]
Generic Structure Dynamic Stress Expansion
Fundamental Change in Approach

The entire process is summarized below

**Equation:**

\[ \begin{align*}
[T_{U}] &= [E_{a}] [E_{a}]^T \\
[RTO_{a}] &= [T] [RTO_{a}] 
\end{align*} \]

Operating Expansion Approach Accounts for Operating Deformations and Actual Loads
Dynamic Displacement Results - Laboratory Structure

Extensive testing and analysis has been performed to validate the proposed methodology.
Dynamic Strain Results - Laboratory Structure

Strain at Location 8

Modal Strain at Location 8

Modal FEA

Expanded

Strain at Location 7

Modal Strain at Location 7

Modal FEA

Expanded

animate

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Validation of Methodology - Laboratory Structure

Prediction of Full Field Dynamic Stress/Strain from Limited Sets of Measured Data

\[ [T_U] = [E_n][E_a]^T \]

\[ [RTO_n] = [T][RTO_a] \]

Pawan Pingle

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Dynamic Stress-Strain
Conventional Approach vs. Alternate Approach

Discretization → Assembly → BC & Loads → Solve for Displacement → Solve for Dynamic Stress-Strain

FE Model

Unknown Operating Loads

Unpredictable Wind Loads

Uncertain Boundary Conditions

Traditional models do not incorporate real loading and true in-operation deformations

Measure Displacement in-situ while Rotating with DIC

Imaging System

Develop Expansion

Expand Operating Data

$[T_u] = [E_u] [E_u]^T$

$[RTO_n] = [T] [RTO_n]$

Operating Expansion Approach accounts for operating deformations and actual loads
Advantages of Alternate Approach

- Loading assumptions are gone
- Actual boundary conditions are included
- Displacement of actual operation is obtained
- Operating data is expanded directly without the approximate estimate of force from limited data
- Dynamic stress-strain obtained for full field
Damage Detection using Full Field Stress Strain

• Model used for expansion with measured damage at limited set of measurement points in operation

\[
\begin{align*}
[M_n] &\quad [K_n] \\
[M_a] &\quad [K_a] \\
\end{align*}
\]

MODEL

\[
\begin{align*}
[M_a] &= [T]^T[M_n][T] \\
\end{align*}
\]

EXPANSION

\[
[T_U] = [U_n][U_a]^g \\
[ERTO_n] = [T][RTO_a] \\
\]

REDUCTION

\[
\begin{align*}
[M_a] &\quad [K_a] \\
\end{align*}
\]

TEST

[Image of a diagram showing the process of damage detection using full field stress strain, with matrices and equations illustrating the model expansion, reduction, and testing process.]

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Damage Detection using Full Field Stress Strain

- Redistribution of load and strain indicate damage

EXPANSION

- $[M_n] = [T]^T[M_n][T]$
- $[K_n] = [T]^T[K_n][T]$

REDUCTION

- $[T_U] = [U_n][U_a]^g$
- $[ERTO_n] = [T][RTO_a]$

MODEL

TEST

FULL FIELD EXPANDED RESPONSE

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Damage Detection using Full Field Stress Strain

- Response change is not noticeable but curvature and strain due to multimode response can be seen
## Damage Detection using Full Field Stress Strain

- **FEA prediction, expansion and actual strain field**

<table>
<thead>
<tr>
<th>Stage 2</th>
<th>Stage 6</th>
<th>Stage 10</th>
<th>Stage 14</th>
<th>Stage 18</th>
</tr>
</thead>
<tbody>
<tr>
<td>FE Anticipated Strain</td>
<td>Measured Expanded Strain</td>
<td>Actual Damaged Strain</td>
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[Graph showing FE Anticipated Strain, Measured Expanded Strain, and Actual Damaged Strain for different stages.]
Damage Detection using Full Field Stress Strain

- FEA prediction, expansion and actual strain field

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