Operational Modal Analysis – *(OMA)*

- Determination of Modal Model by response testing only
  - No measurement of input forces required
  - Measurement procedure similar to Operational Deflection Shapes (ODS)

- Determination of Modal Model under operational conditions
  - In-situ testing

- Used successfully in Civil Engineering applications *(Ambient Modal)*
  - Bridges and buildings
  - Off-shore platforms etc.

- Later introduced to Mechanical Engineering applications *(OMA)*
  - Rotating Machinery
  - On-road and in-flight testing etc.
Operational Modal Analysis *(measurement procedure)*

- Determination of Modal parameters based on natural excitation
- Measurement of responses in a number of DOF’s
  - simultaneously
  - by roving accelerometers with one or more fixed accelerometers as references

- Accelerometers are moved for each data set

- Fixed Reference Accelerometers
Mobility Measurements (Traditional Modal Testing)

- Input Force is measured
- Output Response is measured
- Output is related to Input by FRF estimators
- FRF is independent of the input force

Only the Modes of the System need to be identified

Even if the system is producing noise this is handled by FRF estimators as $H_1, H_2, H_3$

Operational Modal – *(The Combined Model)*

Rotating parts creates Harmonic vibrations

- Rotating Parts
- Computational Noise
- Force Spectrum
- Measurement Noise
- Structural System
- Combined Spectrum

- Output only modal analysis

The “Modes” in the combined spectrum contains information of:

- The system under test (Physical Modes)
- Input Force (Non-physical “Modes”)
- Noise (Non-physical “Modes”)
- Harmonics (Non-physical “Modes”)
Combined System Model *(analysis procedure)*

Model of the combined system is estimated from measured responses.

- **Combined System**
- **Excitation Filter** (linear, time-invariant)
- **Structural System** (linear, time-invariant)

Stationary Zero Mean Gaussian White Noise

Unknown excitation forces

Measured Responses

Modal Model of Structural System extracted from estimated model of Combined System
**Assumptions**

**Mathematical**
- Stationary input force signals can be approximated by filtered zero mean Gaussian white noise
  - Signals are completely described by their correlation functions or auto- & cross-spectra
  - Synthesized correlation functions or auto- & cross-spectra are similar to those obtained from experimental data

**Practical**
- Broadband excitation
- All modes must be excited

**Does not mean that the physical excitation has to be white noise**
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Stochastic Subspace Identification Techniques

SSI with Automatic Mode Estimation

Crystal Clear SSI

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Frequency Domain Decomposition (FDD)

Determination of complete Modal Model from Responses only

FDD procedure:
1. Power Spectral Density (PSD) matrix estimation
2. Singular Value Decomposition (SVD) of PSD matrix
3. Identification of Single Degree of Freedom (SDOF) models from SVD
4. Modal Parameter identification from SDOF models
Projection channels

• Reducing redundant information
  – Only a few independent row/columns exist
  – Many row/columns are linear combinations of the others
  – Much unnecessary (redundant) information exist

• Reduction of linear dependent columns by proper choice of projection channels
  – \([G(:, [p_1 \ p_2])]\)
  – \([p_1 \ p_2]\) : projection channels

\[
\begin{bmatrix}
G_{11} & G_{12} & G_{13} & \ldots & G_{1N} \\
G_{21} & G_{22} & G_{23} & \ldots & \ldots \\
G_{31} & G_{32} & \ldots & \ldots & \ldots \\
G_{41} & \ldots & \ldots & \ldots & \ldots \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
G_{N1} & \ldots & \ldots & \ldots & G_{NN}
\end{bmatrix}
\begin{bmatrix}
G_{1p_1} & G_{1p_2} \\
G_{2p_1} & G_{2p_2} & \ldots & \ldots \\
G_{Np_1} & G_{Np_2}
\end{bmatrix}
\]
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Stochastic Subspace Identification (SSI)

SSI procedure

- Generate **compressed input format**
  - Select total number of modes (structural, harmonics, noise) based on apriori knowledge
  - Select **Identification Class**
    - Unweighted Principal Components (UPC); Principal Components (PC); Canonical Variate Analysis (CVA)

- Estimate Parameters from **Stabilization diagram**
  - Select interval of model order candidates (use SVD diagram)
  - Estimate models (adjust tolerance criteria)
  - Select the optimal model (use validation)

- Select and **link modes across data sets**
Stochastic Subspace Identification (SSI)

- Parametrical Modal estimation requiring *apriory knowledge* of Model Order
- Physical Modes as well as Non-physical Modes are estimated

How can we separate Physical Modes from Non-physical Modes?

*Physical modes are repeated for multiple Model orders!*

Stabilization Diagram

![Stabilization Diagram](image)

- Stable Modes not fulfilling Damping apriori knowledge
  - X Estimated parameters not fulfilling apriori knowledge of damping
  - + Stable modes are repeated in two consecutive models fulfilling user defined criteria
  - X Remaining modes are considered as unstable
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Automatic Mode Extraction using FDD/EFDD

Automatic Mode Extraction using the FDD and EFDD Techniques
Simplifies and speeds up the modal analysis task
Reduces human errors and demands less modal analysis skills
Ease preliminary analysis of a new problem
Allows for unattended testing - Structural Health Monitoring

- Modal Coherence (light blue graph)
  - Defines whether you have a Modal Domain (High) or a Noise Domain (Low)
- Modal Domain (light green graph)
  - A property defined for all modes. Defines the frequency region dominated by the mode
- Excludes deterministic signals from identification (vertical black lines)
SSI with Automatic Mode Estimation

- Searches the stable modes in the SSI Stabilization Diagram
- All stable modes of all estimated models of all test setups are included in the search
- Modal estimates of natural frequencies, damping ratios and modes shapes
- Estimates mean values and standard deviations
Example: Closely spaced modes
- Four test setups
- Two common references
- Automatic Mode Estimation for SSI finds all closely spaced modes between 1 Hz and 2 Hz.
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Stochastic Subspace Identification (SSI)

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- **Physical Modes** as well as **Non-physical Modes** are estimated

How can we separate **Physical Modes** from **Non-physical Modes**?

*Physical modes are repeated for multiple Model orders!*

---

Stabilization Diagram

<table>
<thead>
<tr>
<th>Number of modes in the model</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>+</td>
</tr>
<tr>
<td>5</td>
<td>+</td>
</tr>
<tr>
<td>6</td>
<td>+</td>
</tr>
<tr>
<td>7</td>
<td>+</td>
</tr>
</tbody>
</table>

- **Stable Modes**
- **X** Estimated parameters not fulfilling apriori knowledge of damping
- **+** Stable modes are repeated in two consecutive models fulfilling user defined criteria
- **X** Remaining modes are considered as **unstable**
Stabilization Diagram – What is the problem?

- Parametrical Modal estimation requiring **apriory knowledge** of Model Order
- **Physical Modes** as well as **Non-physical Modes** are estimated

How can we separate Physical Modes from Non-physical Modes?

*Physical modes are repeated for multiple Model orders!*

Stabilization Diagram

1. The maximum number of modes must be higher than the number of physical modes
2. The higher the model order, the more noise (computational) modes will be found
3. The Stabilization Diagram then becomes difficult for the user to interpret
Crystal Clear SSI (CC-SSI)

Problem

- Stabilization Diagrams need to be evaluated for higher number of modes than the number of physical modes
- Classical stabilization diagrams often “dirty” applied to practical examples
- What are modes and what are not?
Crystal Clear SSI (CC-SSI)

Classical Stabilization Diagram

Intelligent-automated use of the Stabilization Diagram

- Sorting physical- from noise modes becomes easy and safe
- Influence from noise modes modes on the physical modes are minimized

Stabilization Diagram Using CC-SSI
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General Conclusions:

- **Dedicated System** for Operational Modal Analysis offering *reliable* estimation of modal parameters *without* known input force

- The method makes modal testing *easier* on *large* structures as *no* elaborate excitation is needed

- Use *data* acquired during operation for extraction of modal data

- The technique *currently used in civil engineering* *now* to be introduced into mechanical applications
Conclusion (advantages)

- **No elaborate fixturing** of structures, shakers and force transducers
  - No test rigs needed
  - Short setup time
  - No dynamic loading from shakers and stingers
  - No crest factor problems as when using hammers
  - No potential destruction of structure
- **Modal model can represent** real operating conditions
  - True boundary conditions
  - Actual force and vibration levels
- **Only natural random** or unmeasured artificial excitation required
- **No interference or interruption** of daily use
- **Modal testing can be applied** in parallel with other applications
Conclusion (concerns)

- Unscaled (Non Calibrated) Modal Model
  - No Forced Response and Modification Simulations
- More Operator Skills required
  - Some apriori knowledge is advantageous
  - Pre-analysis is often needed
  - New technique to most engineers
Like to learn more?

IOMAC 2009 - Porto Novo (Ancona, Italy), 4-6 May 2009

www.iomac.org
1st International Operational Modal Analysis Conference
History 2005

> 80 Papers Presented

>140 Participants

Exhibition presenting Equipment for Modal Analysis
Like to learn more?

Beginner?

A pre-conference course on Operational Modal Analysis is offered on Monday 4 May by

- Dr. Carlos Ventura, Prof. Univ. British Columbia, Canada
- M.Sc. Svend Gade, Prof. Brüel & Kjær University, Denmark.

This is a one-day short course covering operational modal analysis based on unmeasured excitation, for example natural excitation.
Like to learn more?

Next SVS Webinars

- **Thursday 11 June 2009** - at 10 am & 6 pm CE(S)T: Introduction to Operational Modal Analysis including the new revolutionary Crystal Clear SSI.
- **Monday 21 September 2009** - at 10 am & 6 pm CE(S)T: OMA estimators and the latest improvements in SSI with examples from mechanical- and civil engineering.
- **Monday 23 November 2009** - at 10 am & 6 pm CET: Topic to be announced.

And follow other activities on [www.svibs.com](http://www.svibs.com)
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Thank you for your attention

Copy of the material will be available in a few days