A benchmark for identification of structural modifications and inelastic impacts: the structure, test data and an example solution

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Outline

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1. Introduction
   - Motivation
   - Other SHM benchmarks
   - This work

Motivation

- A great variety of innovative techniques has been proposed for global structural health monitoring (SHM).
- Their actual effectiveness is hardly comparable due to different
  - involved assumptions,
  - tested structures,
  - identification examples and goals.

We propose a small and simple lab-size, purely experimental benchmark for testing of algorithms in two typical SHM problems:

1. identification of structural modifications,
2. identification of inelastic impacts.

Other SHM benchmarks

1. ISAC-ASCE Benchmark Problem
   - uses a FE model of a 4-story, 2×2-bay steel frame (120 DOFs)
   - different damages/modifications simulated (simulated measurements and the FE model available for download)
   - experimental data (collected in 2002 using a scaled lab model) are no longer online, main benchmark homepage is offline
2. IABMAS Benchmark Problem
   - analytical benchmark problem in SHM of medium-span bridges
   - experimental measurements of a healthy and damaged 18×6 ft grid lab model and “official” numerical model are available online
3. Guangzhou New TV Tower Benchmark
   - real-world output-only measurements taken during construction of the Guangzhou New TV Tower (∼600 m height)
   - no FE model of the structure is provided
   - no damaged structure (measurements of incomplete structure)

This work

We propose a small and simple benchmark for standardized testing of algorithms in two typical SHM problems:

- identification of structural modifications (mass or stiffness),
- identification of inelastic impacts (mass and velocity).

Main features

1. purely experimental approach
   - only experimental measurements (impulse responses) provided
   - no “official” FE model (technical specifications online)
2. small and simple lab-size structure (truss-like)
   - modifications/impacts can be actually implemented
   - fluctuations of the environmental factors can be neglected
   - a relatively comprehensive instrumentation can be used (to shift the focus from structural modeling to identification)

Outline

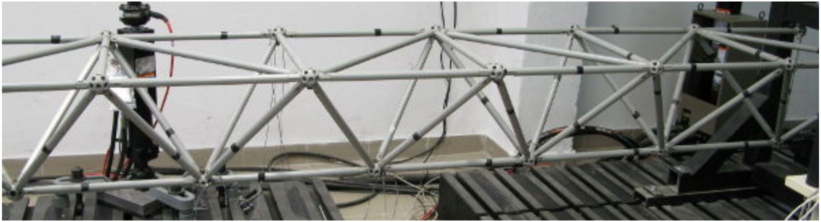
2 Benchmark

- The structure
- Experimental characteristics (unmodified structure)
- Identification cases
- Evaluation of results

The structure

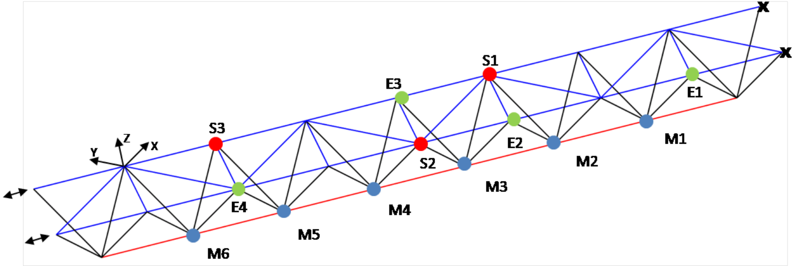
a commercially available truss-like node/tube system (MeroForm)

- length 4 m
- 70 elements
- 26 nodes
- weight 32 kg



Experimental characteristics

Original unmodified structure



A set of quasi impulse responses is provided:

excitation	M1. . . M6 (xyz-directions)
	E1. . . E4 (z-direction)
response	M1. . . M6 (xyz-directions)
	S1. . . S3 (z-direction)

Excitation (modal hammer) and response (acceleration) is measured. Displacement is computed.

Identification cases

Three scenarios

Structural modifications

1. Unknown nodal mass modifications
   - Single nodal mass (location known, mass unknown)
   - Two nodal masses (location known, masses unknown)
2. Unknown stiffness modification
   - *in preparation...*

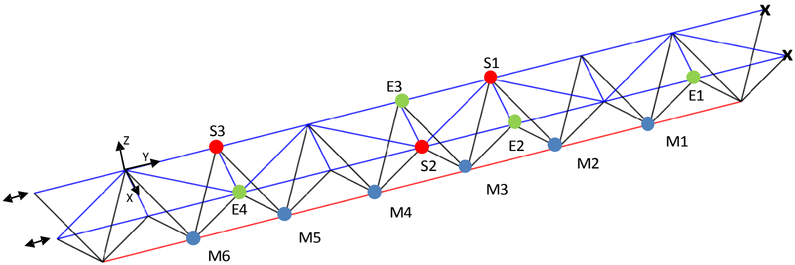
Inelastic impacts

3. Unknown inelastic impacts
   - Single inelastic impact[a] (location and direction known, mass/velocity unknown)

[a] Simulated by fixing a nodal mass and applying an initial excitation.

Identification cases

Measured responses



Measured responses (modified/impacted structure)

A set of testing quasi impulse responses is provided:

excitation E1. . . E4 (z-direction)

response S1. . . S3 (z-direction)

Excitation (modal hammer) and response (acceleration) is measured. Displacement is computed.

Evaluation of results

Evaluation will be performed with respect to all solutions:

$$c := \frac{c_1 - \bar{c}_1}{\sigma_{c_1}} + \frac{c_2 - \bar{c}_2}{\sigma_{c_2}} + 0.25\frac{c_3 - \bar{c}_3}{\sigma_{c_3}},$$

where

- c_1 relative identification accuracy $c_1 := \sum_i \frac{\|\mathbf{m}_i^{(\text{actual})} - \mathbf{m}_i^{(\text{identified})}\|^2}{\|\mathbf{m}_i^{(\text{actual})}\|^2}$
- c_2 number of sensors and testing excitations used for identification $c_2 := N_\text{E} N_\text{S}$
- c_3 number of source lines of code

Identification time

- important and interesting
- not practical as a criterion (different computers, compilers, libraries, environments, etc.)

Outline

3. An example solution
   - Quasi static equation of motion
   - Structural modifications
   - Example results

Quasi static equation of motion

original unmodified structure

$$\mathbf{M}\ddot{\mathbf{u}}^{\mathrm{L}}(t) + \mathbf{C}\dot{\mathbf{u}}^{\mathrm{L}}(t) + \mathbf{K}\mathbf{u}^{\mathrm{L}}(t) = \mathbf{f}(t)$$

$$\mathbf{D}(\omega)\mathbf{u}^{\mathrm{L}}(\omega) = \mathbf{f}(\omega) \qquad \mathbf{u}^{\mathrm{L}}(\omega) = \mathbf{H}(\omega)\mathbf{f}(\omega)$$

where

$$\mathbf{D}(\omega) = -\omega^2\mathbf{M} + \mathrm{i}\omega\mathbf{C} + \mathbf{K} \qquad \text{(dynamic stiffness matrix)}$$

$$\mathbf{H}(\omega) = \mathbf{D}^{-1}(\omega) \qquad \text{(dynamic compliance matrix)}$$

Submatrices of $\mathbf{H}(\omega)$ can be obtained experimentally:

- separately for each ω as response vectors to harmonic excitations (time-consuming, accurate) or
- for all ω at once via the FFT of an impulsive excitation and the responses (quick, simple instrumentation, less accurate).

Structural modifications

an approach based on the Virtual Distortion Method (VDM)

Let $\mathbf{x} = (\mathbf{m}, \boldsymbol{\Delta}\mathbf{AE})$ collect the unknown modification parameters. The quasi static equation of motion of the modified[1] structure,

$$\left[-\omega^2\mathbf{M} - \omega^2\Delta\mathbf{M}(\mathbf{x}) + \mathrm{i}\omega\mathbf{C} + \mathbf{K} + \Delta\mathbf{K}(\mathbf{x})\right]\mathbf{u}(\omega,\mathbf{x}) = \mathbf{f}(\omega),$$

yields the equation of motion of the unmodified structure

$$\mathbf{D}(\omega)\mathbf{u}(\omega,\mathbf{x}) = \mathbf{f}(\omega) + \mathbf{p}(\omega,\mathbf{x}),$$

where the modifications are modeled with pseudo loads

$$\mathbf{p}(\omega,\mathbf{x}) = \Delta\mathbf{D}(\omega,\mathbf{x})\mathbf{u}(\omega,\mathbf{x}) \qquad (\star)$$

and $\Delta\mathbf{D}(\omega,\mathbf{x}) = -\omega^2\Delta\mathbf{M}(\mathbf{x}) + \Delta\mathbf{K}(\mathbf{x})$. Moreover,

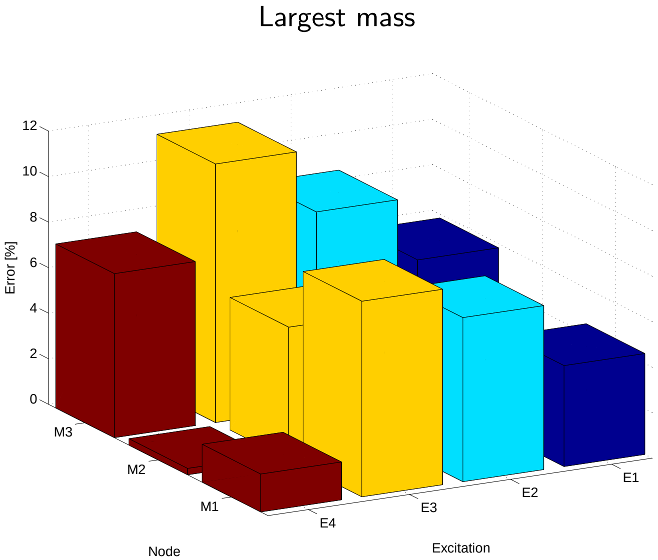
$$\mathbf{u}(\omega,\mathbf{x}) = \mathbf{u}^{\mathrm{L}}(\omega,\mathbf{x}) + \mathbf{H}(\omega)\mathbf{p}(\omega,\mathbf{x}). \qquad (\star\star)$$

Finally, substitution of $(\star\star)$ into $(\star)$ yields

$$\left[\mathbf{I} - \Delta\mathbf{D}(\omega,\mathbf{x})\mathbf{H}\right]\mathbf{p}(\omega,\mathbf{x}) = \Delta\mathbf{D}(\omega,\mathbf{x})\mathbf{u}^{\mathrm{L}}(\omega,\mathbf{x}).$$

[1] For an inelastically impacted structure $\mathbf{f}(t) = mv\mathbf{e}_k\delta(t)$.

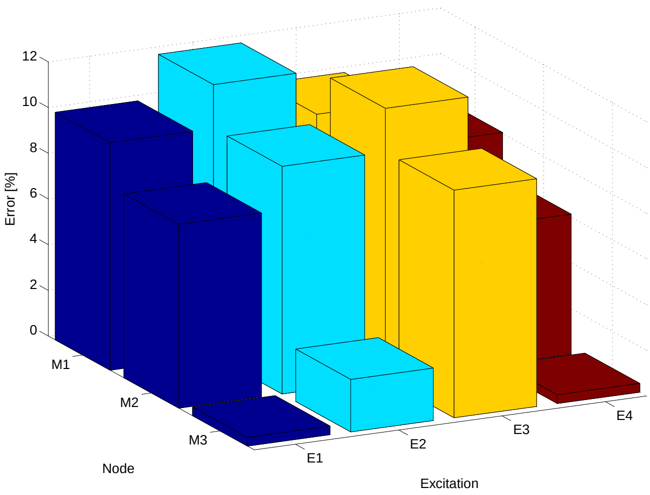
Example results
single nodal mass modification (three sensors)



Example results

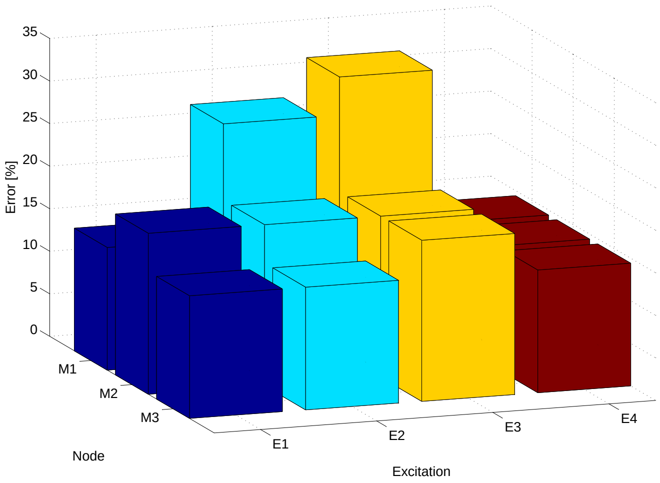
single nodal mass modification (three sensors)

Middle mass



Example results
single nodal mass modification (three sensors)

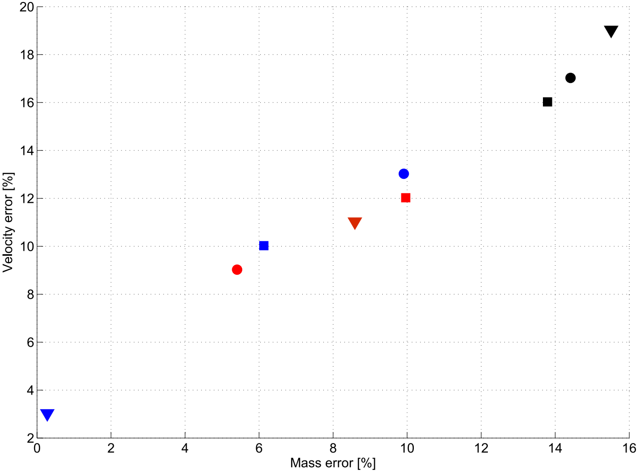
Smallest mass



Example results

identification of inelastic impacts (three sensors)

node M1	node M1	node M1
▽ largest mass	□ middle mass	◯ smallest mass



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Conclusions

- A purely experimental, lab-size benchmark is proposed for testing of algorithms for
  - identification of structural modifications
  - identification of inelastic impacts
- All the data are available online for download

  `http://www.ippt.gov.pl/~ljank/benchmark.php`

  You are invited to participate and test your identification algorithms.

Besides, an example model-free identification approach based on the Virtual Distortion Method (VDM) is proposed.

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