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Guidelines for OMA in Civil Engineering

Edited by Carlo Rainieri

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IOMAC Association

The aims of the association are to study, analyze, and apply operational modal analysis to all types of structures and mechanical systems. To pursue this aim, the IOMAC shall:

1. Promote the generation and dissemination of technical and scientific information within its field of activity, fomenting the teaching and training at all levels of subjects related to operational modal analysis.
2. Foment the collaboration and transfer of the results between industry and public as well as private research groups.
3. Cooperate with administrations and with the groups, associations, and industrial sectors involved, in the preparation and execution of projects related to modal analysis.
4. Work together with other like societies both national and international in the undertaking of said activities.
5. Meetings, congresses, conferences, seminars, courses, workshops and exhibitions. In particular, the International Operational Modal Analysis Conference (IOMAC) shall be held every two years.
6. Editing (printed or electronic) scientific publications and techniques, bulletins, mailing lists or any other means of dissemination or exchange of scientific and technical information.
7. Awarding of financial assistance and prizes.
8. General undertaking of any activity that could help in the achievement of the aims set by IOMAC

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In memory of Reto Cantieni,
his contributions to IOMAC and OMA,
and his practical approach to the discipline.
He spent his last working energies
by contributing to these Guidelines.

Guidelines for OMA in Civil Engineering

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Technical Guidelines Development Committee

Carlo Rainieri, Chair, National Research Council of Italy, Italy
Manuel Lopez Aenlle, Member, University of Oviedo, Chair of the IOMAC Association, Spain
Ruben Luis Boroschek, Member, University of Chile, Chile
Anders Brandt, Member, Aarhus University, Denmark
Rune Brincker, Member, Technical University of Denmark, Denmark
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Jacek Grosel, Member, Wroclaw University of Technology, Poland
Filipe Magalhaes, Member, University of Porto, Portugal
Julie Regnier, Member, Cerema, France
Dmitri Tcherniak, Member, Brüel & Kjær, Denmark

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CONTENT

1. INTRODUCTION

Operational Modal Analysis (OMA) [1, 2] techniques aim at the experimental estimation of modal properties of structures from processing of the structural vibration response only.

Vibration measurements are usually performed under operational conditions, thus making OMA very attractive because of its minimum interference with the normal use of the structure, and its affordable cost. In addition, the resulting modal property estimates are representative of the actual behavior of the structure in its operational conditions.

Data processing can be carried out either in the time or frequency domain. The results (modal properties) can be used for structural assessment with respect to dynamic excitations and, under some circumstances, for structural health and performance assessment.

The present guidelines are aimed at providing recommendations for planning and execution of OMA tests, and for data processing aimed at the estimation of modal properties of structures from measurements of their vibration response. The present guidelines, in particular, focus on civil structures, although many of its provisions and recommendations are applicable to any mechanical structure, as well.

2. AIMS AND SCOPE

The present guidelines are focused on OMA of civil engineering structures. The guidelines provide general recommendations for test planning and execution, criteria for the selection, maintenance, and installation of measurement equipment, for data pretreatment, processing and validation. Moreover, an overview of possible post-processing is given including, among the others, Finite Element (FE) model updating and modal property tracking for vibration-based Structural Health Monitoring (SHM).

The herein reported recommendations are valid in general, but their application has to take into account the peculiar characteristics of the structure under test.

Recommendations and criteria reported in the present document are not compulsory and they have no legal value. The present guidelines, indeed, summarize good practices in order to guide technicians towards field applications of OMA to civil engineering structures.

3. TERMS AND ABBREVIATIONS

ADC	Analog-to-Digital Converter
dB	Decibel
DC	Direct Current

DOF	Degree of Freedom
DR	Dynamic range
EFDD	Enhanced Frequency Domain Decomposition
ERA	Eigensystem Realization Algorithm
FDD	Frequency Domain Decomposition
FE	Finite Element
FFT	Fast Fourier Transform
FRF	Frequency Response Function
FSDD	Frequency Spatial Domain Decomposition
ITD	Ibrahim Time Domain
LSB	Least Significant Bit
LSCE	Least Squares Complex Exponential
LSCF	Least Squares Complex Frequency
MAC	Modal Assurance Criterion
MDOF	Multi Degree of Freedom
MSF	Modal Scale Factor
NRFD	Normalized Relative Frequency Difference
OMA	Operational Modal Analysis
OMAH	Operational Modal Analysis with Harmonic excitation
p-	Poly-reference
PCA	Principal Component Analysis
PSD	Power Spectral Density
SDOF	Single Degree of Freedom
SHM	Structural Health Monitoring
SOBI	Second Order Blind Identification
SSI	Stochastic Subspace Identification
SVD	Singular Value Decomposition

4. MEASUREMENT PLANNING AND EXECUTION

OMA test planning can rely on either a physical insight of the dynamic behavior of the structure under investigation (expected natural frequencies and corresponding mode shapes) or numerical modeling of the structure itself. The latter approach is more time consuming but it can be a valid starting point in the absence of any prediction capability based on previous experiences in testing of similar structures. Nevertheless, it is worth pointing out that the preliminary numerical model might yield very different results with respect to the experimental test depending on modeling assumptions and uncertainties. In any case, if a FE model of the structure under test is used for test planning, both natural frequencies and modal displacements should be analyzed in order to properly design the OMA test and select the most appropriate modal parameter estimation procedure.

Engineering judgement always plays a critical role in test planning, and caution must be adopted whenever the test engineer is not confident with the expected dynamic behavior of the structure under test; increasing the spatial resolution of measurements and the number of measured degrees of freedom are possible countermeasures to deal with poor confidence.

4.1. Sensor and measurement system selection

Sensors are also called transducers because they turn physical or mechanical quantities into electrical signals, which are discretized afterwards in order to be stored and processed. The typical measurement equipment includes the sensors (to be installed on the structure under test), a signal conditioning unit, a data acquisition unit (responsible for the digitization of the analog signals coming from the sensors), a computer for data storage and processing. The previously mentioned components can be associated with individual physical devices, or integrated into other components (this might be the case, for instance, of the signal conditioning unit, which can be embedded into either the sensor or the data acquisition unit, and of the data acquisition unit, which can be embedded into the sensor, as in the case of digital sensors). Commonly used sensors for OMA testing are accelerometers, velocimeters, (dynamic) strain gauges, even if different sensor types can be applied (for instance, GPS, fiber optic sensors, and so on) provided that they have adequate characteristics. Moreover, for a given sensor type, different classes can be identified based on the technology or physical principle adopted for their fabrication. As a result, it is possible to distinguish capacitive sensors, resistive sensors, piezoelectric sensors, electromagnetic sensors, fiber optic sensors, and so on.

Another common distinction is between wired and wireless sensor systems. This distinction actually refers to the way data are transferred from the sensors to the data processing unit. Wireless sensor systems are digital sensors that transfer the signals avoiding the physical connection by cables between sensors and data acquisition unit. The transferred data are, therefore, already digitized: digitization is indeed carried out by a data acquisition unit embedded into the sensor and this poses some challenges in data processing. In particular, the main challenge refers to the synchronization of measurements. While this is automatically achieved by wired systems, synchronization might be an issue when wireless sensor systems are used. However, synchronization might be also an issue in the presence of multiple wired systems not synchronized with each other. Synchronization is important:

- if the mode shapes and/or modal strains are of interests (this is often the case);
- If the OMA algorithm uses spatial information: for instance, FSDD in frequency domain, and SOBI in time domain use spatial information to separate the modal contributions before natural frequency and damping ratio estimation. Synchronization is important also for OMA methods dealing with normal modes only: this is the case, for instance, of SOBI.

Synchronization error results in mode shape error: for a mode with natural frequency f_r (measured in Hz), the phase error of the mode shape can be estimated as $\varphi_{error}=2\pi \cdot f_r \cdot t_{sync}$ (expressed in rad) or $\varphi_{error}=360 \cdot f_r \cdot t_{sync}$ (in degrees), where t_{sync} (in sec) is the synchronization error. However, the previous expressions also show that synchronization is easier to achieve at low frequencies, such as those associated with the fundamental modes of long span bridges and high-rise structures.

Different solutions exist (GPS, WiFi, etc.) to synchronize wireless sensor systems or multiple wired measurement systems. However, those solutions must be carefully considered to assess their effectiveness in the actual testing conditions. As an alternative, analytical approaches to synchronize the signals after measures should be adopted [3].

Wireless sensor systems are definitely an attractive option for OMA tests because of the advantages they offer (reduced installation time and efforts associated with the absence of cables, current battery capacity able to fulfill the requirements of OMA tests in terms of operational durability, reduced noise pick up from the environment because of the absence of long cables). On the other hand, issues such as effective data transfer over limited distances, possible interferences affecting data transfer, and the finite duration of batteries (power supply becomes an issue when OMA is applied in the context of continuous SHM) require specific considerations at the test design stage.

A solution able to combine most of the advantages of wired and wireless sensor systems is represented by distributed measurement systems. They allow minimizing the length of sensor cables, but different data acquisition modules must be connected by LAN cables, if wired, or to GPS, if wireless, to ensure data synchronization. The quality of synchronization in distributed measured systems connected by LAN depends on the number of connected modules and the distance from each other and/or from the master.

A preliminary analysis of the technical datasheets of sensors is fundamental to assess their adequacy for OMA tests. The very little amplitude of vibrations over a relatively wide frequency range is the main difficulty associated with measurement execution for OMA. Taking into account that accelerometers are the most used sensors for OMA, the following technical features must be checked (in absolute terms, if possible, or comparatively) in the test design phase:

- ***Sensitivity*** (or gain): it is defined as the minimum input of physical parameter that creates a detectable output change. However, the smallest detectable signal is also limited by the noise generated in the electronics. From a general point of view, a high gain should be preferred since an amplified signal minimizes the noise effects associated with the transmission over cables. Besides, it is important to verify that the maximum sensor output has a level fitting the recorder maximum input, so that the sensor dynamic range is optimally used. A sensitivity of accelerometers of 10 V/g or higher is recommended. A lower value (but not lower than 1 V/g) can be considered only for those structures exhibiting significant operation excited vibrations (e.g. traffic): however, a pre-test to assess the ability of the sensor to resolve operational vibrations is highly recommended.
- ***Dynamic range***: often expressed in dB, it is the ratio between the largest and the smallest signal the sensor can measure; the best vibration sensors have a dynamic range higher than 150 dB, but dynamic range in the order of 100-120 dB is also suitable. As reference values for the average vibration levels in operational conditions, the user can consider: 1E-6÷1E-5 g for bridges without traffic or low-rise buildings, 1E-5÷1E-4 g for bridges in the presence of traffic or high-rise buildings.
- ***Full-scale range***: it identifies the minimum and maximum values of the physical quantity the sensors can measure. With a few exceptions (for instance, wind turbine blades), a full-scale range of ±0.5 g or lower is suitable for OMA tests.
- ***Resolution***: it represents the smallest incremental change of physical quantity that leads to a detectable change in the sensor output. A value of 0.00001 g or lower should be considered for general OMA applications based on acceleration measurements; this value can be increased in the case of bridges or flexible structures.
- ***Frequency range***: it represents the frequency range over which the sensor gives its output without distortion; it must comply with the minimum and/or maximum frequency of interest of the structure under test. With the exception of very flexible structures (for instance, high-rise buildings consisting of more than twenty floors, wind turbines, long span bridges and floating structures) requiring a frequency range starting from DC, a frequency range of 0.5-50 Hz is suitable for most OMA applications.

- ***Spectral noise***: it plays a primary role in determining the capability of the sensor to properly resolve the ambient vibration response of the structure. In fact, if the signal to be recorded is very small, it may drown in the electronic noise of the sensor. The sensor self-noise depends on the frequency. A spectral noise of 1 μg/√Hz or lower over the frequency range of interest is recommended for general OMA applications, even if it can be increased by an order of magnitude (up to 20 μg/√Hz) in the case of bridges and other flexible structures.
- ***Cross axis sensitivity***: it quantifies the sensor sensitivity to a motion perpendicular to the main axis. Accelerometers for modal testing typically show a low transverse sensitivity, in the order of 2% or less.

In addition, the following technical features of the data acquisition system have to be checked in the test design phase:

- ***Resolution***: it can be defined as the smallest step that the digitizer can detect. It corresponds to one change of the LSB. For high dynamic range digitizers, the order of magnitude of resolution is about 1 μV. The ***number of bits*** is also sometimes referred to as resolution. However, most ADCs have an internal noise higher than one count: in this case, the number of noise free bits, rather than the total bit number, yields the effective resolution. Nevertheless, 24 bit resolution is usually adequate for applications.
- ***Noise level***: it is related to the number of bits occupied by noise when the input is zero.
- ***Analog anti-aliasing filter***: it is necessary to prevent that high frequency components are mirrored at low frequencies.
- ***Dynamic range***: it is defined as the ratio between the largest and the smallest value the digitizer can acquire without significant distortion. It is usually expressed in dB. Taking into account that the lowest bits often contain only noise, the dynamic range is also defined as the ratio between the largest input voltage and the noise level of the digitizer. This number might depend on the sampling frequency. Good digitizers currently have a dynamic range (DR_{ADC}) higher than 100 dB. The dynamic range is related to the number of effective bits by the following equation allowing to estimate the number of effective bits $N_{bit,eff}$ (or, alternatively, the noise level) from the dynamic range of the digitizer:

$$DR_{ADC} = 20 \cdot log(2^{N_{bit,eff}-1}) \approx 6 \cdot \left(N_{bit,eff} - 1\right) \qquad (1)$$

- ***Sampling rate***: it gives the number of collected samples per second. The sampling rate of the digitizer defines the upper bound of the ***frequency range*** under investigation. For the majority of applications of OMA in civil engineering, a sampling rate of 100 Hz is satisfactory. However, special structures may require higher sampling rate. It is worth noting that the sampling rate only defines the upper bound of the frequency range. However, the lower bound must be checked, too, to verify that it is suitable to identify the fundamental frequencies of the structure under test, in particular in the case of structures characterized by very low fundamental frequencies (long span bridges, high-rise buildings): in these conditions a frequency range starting from DC is recommended. In addition to the sampling rate, it is worth checking that the data acquisition system ensures simultaneous sampling in order to preserve the phase information among all the measurement channels.

- ***Cross-talk***: this occurs when a signal recorded in one channel affects other channels. The amount of cross-talk is expressed in dB and means how much lower the level in a channel is in the neighboring channels. A good quality 24-bit digitizer has 120 dB of damping or better. In this respect, multiplexed systems should be avoided for OMA.

It is worth mentioning that the above technical features separately refer to analog sensors and data acquisition systems. However, in the case of digital sensors, transducer and digitizer are joined into a single device. Either in the case of analog or digital sensors, the quality of data is strictly related to the features of sensors and digitizer, but it also depends on their appropriate coupling (adopted measurement scheme, sensor output fitting the digitizer input voltage, and so on).

Versatility (possibility of selecting different measurement schemes, such as single-ended or differential, or of acquiring signals from sensors of different type), robustness to varying environmental conditions, portability, low power consumption and possibility of battery operation are additional factors to consider in the choice of the measurement equipment for field testing.

Cabling between sensors and measurement device deserves particular attention: if differential measurement systems are used, these must have a sufficiently high common mode rejection ratio, while inappropriate selection of the measurement scheme can yield severe ground loop problems with single-ended systems. The advantage of using single-ended or pseudo-differential systems is the possibility to have twice the channels with respect to differential systems. However, the latter are often the best option when sources of common-mode voltage noise (such as 50/60 Hz signals from power lines, power supply ripple or electromagnetic fields) are present.

When wired measurement systems are used, cables and connection must be carefully checked to avoid the introduction of noise. In particular, defective connectors can yield noise spikes, while poorly shielded cables yield very noisy measurements (see also Section 6.1). In the presence of wired sensors with integrated electronics, cables may be very long without any significant signal attenuation or heavy noise effects. However, cables no longer than 100 m are recommended: if longer distances have to be covered, distributed architectures should be considered so that cable length does not exceed the recommended value; in any case, cable length must be defined in compliance with the manufacturer's guidelines. As an alternative, wireless sensor systems can be considered.

4.2. Sensor and measurement system checks

Most of the sensors for vibration measurements are very robust: deviations in time with respect to the nominal values of technical features reported in the datasheet are usually very small, with negligible influence on measurement results. However, from time to time or for particular applications sensor calibration might be needed. Calibration (of sensors as well as data acquisition systems) is usually carried out by the manufacturer and it must comply with reference standards, such as the ISO 16063 Code [4]. However, this is commonly a very expensive task. As an alternative, unless a recently issued calibration certification is necessary, the test engineer can apply the so-called back-to-back calibration with a reference sensor to evaluate the sensitivity of the sensor under test and compare it with the nominal value reported in the technical sheet. Sensors can be accepted for use even in the presence of small sensitivity deviations, provided that they cause an error in the estimation of modal displacements no larger than ±3%.

Quantifying the noise floor of the measurement equipment might be significant (for instance, to compare different measurement chains). If two sensors of the same model from the same manufacturer are available and they are connected to the same digitizer, the noise floor can be estimated by installing the two sensors close each other in a way that they measure the same DOF. The SVD of the resulting 2-by-2 PSD matrix provides the noise floor. A noise floor in the order of -140 dB (ref.: 1 m/s^2) in the frequency range 0÷100 Hz is recommended for OMA tests.

4.3. Sensor layout and installation

Sensor layout and attachment method have an influence on the identifiability of the modal properties of the structure under test. In particular, closely spaced modes can be identified provided that the sensor location enables collecting a sufficient amount of independent information. To this aim, sensors have to be installed according to different orientations and in appropriate locations, depending on the characteristics of the modes to identify. Indeed, inappropriate sensor locations are in the vicinity of nodes of mode shapes or measuring the same DOF, so that no new independent information is added.

It is clear from the above the importance of applying engineering judgement in the definition of the sensor layout. Alternative approaches are based on a FE model of the structure and/or optimal sensor location algorithms. However, the results obtained from the application of those methods depend on the adopted criteria and optimization techniques, leading to different possible layouts. Thus, those techniques can support the definition of the test layout but a careful planning by the test engineer and a certain amount of physical insight still play a relevant role in the definition of layouts able to maximize the observability of the modes and the amount of information provided by the sensors.

The sensor layout is defined by taking into account the objectives of the modal identification test, the number of available sensors, and the sought information about the mode shapes or their characteristics, which may lead to different requirements in terms of spatial density of the sensors. As a general recommendation, at least 6÷8 sensors should be appropriately placed on the structure under test in order to identify its fundamental modes. If higher modes are also of interest, the number of sensors should be increased in order to have sufficient spatial resolution to distinguish the mode shapes associated with different modes, especially in the case of closely spaced modes. In any case, the adopted sensor layout must ensure the observability of the modes of interest (for instance, bending as well as torsional modes).

Even if the sensor layout varies from structure to structure and it can be also refined during the test if the measurements do not appear satisfactory at a first preliminary analysis, some recurrent schemes for sensor placement can be identified. Under the assumption of rigid floors in building-like structures, at least three sensors have to be installed on a floor. In order to ensure the observability of both translational and torsional modes, the sensors have to be installed in two orthogonal directions and in opposite corners of each instrumented floor. Installing the sensors on, at least, two distinct floors allows, in principle, the identification also of some higher modes. When the tested structure is a bridge, both vertical and lateral (as well as longitudinal, if appropriate) components of acceleration have to be measured in order to ensure the identification of lateral and vertical bending modes. Moreover, installation of couples of sensors measuring the vertical component of acceleration at the same abscissa along the main axis of the bridge but in symmetrical points with respect to it ensures the observability of torsional modes.

The previously suggested layouts represent only crude guidelines for the installation of the sensors. The actual test layout has to be defined by taking into account all the previously discussed issues, the characteristics of the tested structure, and those of the applied OMA method (Section 7).

If the number of available sensors is not sufficient to obtain the desired spatial resolution for the mode shape estimates, multi-layout tests can be arranged. The mode shape estimates obtained from the selected layouts cannot simply be glued together, because they are recorded at different times under different ambient excitations, but an appropriate scaling constant has to be applied to the modal vectors obtained from the additional layouts with respect to the reference one. Thus, an additional step is required for normalization between the different layouts, for which reference sensors are necessary. In other words, the estimation of the scaling constant requires that a number of sensors (called reference sensors) remain in the same position during all tests, while the others (called roving sensors) are moved until the structural response is measured at all the desired locations. The scaling factors can be finally determined.

In general, the reference sensors should be in a minimum of four, with a minimum of two sensors in each direction significant to the observability of the modes. Moreover, they should be associated with non-negligible modal displacements in each direction. Assuming that a sufficient number of properly located and oriented reference sensors are available, there are two basic philosophies to process the multi-layout data:

- Post-identification assembly: the modal parameters are identified separately for each sensor layout. Based on the identified frequencies and mode shape parts at the reference sensors the modes are tracked and paired between the different layouts. For each mode, the mode shape parts from each layout are re-scaled based on the information from the reference sensors and glued together to obtain the global mode shapes;
- Pre-identification assembly: the normalization step with respect to the reference sensors takes place before the modal parameter identification, either directly on the data or in the early stages of the applied identification algorithm. Then, the global modal parameters are obtained in one run on the merged and normalized data from all the sensor layouts together.

Both philosophies have their advantages and shortcomings. The post-identification assembly is conceptually simple, but requires many modal parameter identifications (one for each sensor layout) and their pairing between the setups, which can be cumbersome if the number of layouts is large. Difficulties may arise for closely spaced modes, and when modes cannot be identified in some of the layouts. The pre-identification assembly requires more sophisticated signal processing, but the modal parameter identification is carried out only once without the need of mode pairing between the different layouts. Difficulties may arise when the modes change between the layouts (e.g. due to temperature changes).

The simplest approach for post-identification assembly of the mode shapes consists in determining the scaling factors for the mode shapes of each layout with respect to a chosen layout, such that the mode shape parts at the reference sensors match in a least-squares sense. Then, the mode shapes of the layouts are re-scaled and glued together. As previously mentioned, the use of a fairly large number of reference sensors is recommended in order to ensure the availability of a number of reasonably large mode shape components for all the modes. However, it is also worth noting that having too many layouts may become tricky, since not all modes might be excited in all setups. In addition, if tests are carried out under different environmental conditions, data interpretation might become very challenging. Thus, the appropriate choice of number and positions of the reference sensors is critical for the success of the test, and optimal sensor placement algorithms can support those tasks. As an alternative, instead of choosing one layout for the normalization, a more global least-squares approach can be applied, as described for example in [5].

The pre-identification assembly usually depends on the applied modal parameter identification method. In SSI, the normalization can be made by means of the observability matrix parts corresponding to the reference sensors of each layout, as described in [6]. In FDD, the power spectral densities can be re-scaled prior to the identification, as described in [7].

Once the sensor layout has been defined, accelerometers can be mounted by a variety of methods, including screwing, magnets, adhesive. The main drawbacks with screwing are the higher difficulty in moving the sensors in different positions of the structure and their impact (in particular, if sensors are installed in buildings). However, it is important that the sensors are installed in a way to ensure an as much stiff as possible connection. In fact, the connection between sensor and structure acts like a spring, and it can narrow the useful frequency range of the sensor. Stud or screwed bolts ensure a very stiff connection, but magnet or adhesive mounting can be an option: the test engineer should refer to the manufacturer’s recommendation to select the appropriate mounting method.

A smooth and flat surface of the structure at the desired sensor locations is also required for the same reasons mentioned for mounting. A well-prepared surface allows the sensor to be installed normally to it and with a very stiff contact between sensor and structure. On the contrary, a rough surface can lead to misalignments or poor contact, causing a loss of stiffness of the connection.

When only uniaxial accelerometers are available and the structural response at a given location has to be measured in different directions, very stiff cubic supports (made of steel or aluminum) can be used to install two or three monoaxial accelerometers along orthogonal directions.

Please, note that the selection of the mounting method depends on several factors, such as accessibility, expected amplitude of vibration and frequency range, portability, and surface type and conditions. Additional recommendations can be found in ISO 5348 [8] for accelerometers. In any case, the mounting method and the reason for its choice must be documented in the test report (Section 11).

4.4. Measurement execution

Once the measurement equipment has been selected and the sensor layout defined, measurement execution requires appropriate consideration of the following aspects:

- Sampling frequency setting;
- On-line filtering and decimation;
- Total record length;
- Nature of the input: ambient vibrations (wind, traffic, microtremors) alone, or in combination with additional artificial excitation (sudden release, weight drop, vehicle passing on a bumper, pedestrians, hammer impact, forces applied by shakers), which can eventually require triggering;
- Storage methods and file format.

The appropriate setting of sampling frequency is critical. It has to be set depending on the maximum frequency of the structure under test. As a rule of thumb, it can be set as 2.5÷3 times the maximum frequency of interest. For ordinary buildings and bridges, a sampling frequency of 100 Hz is usually appropriate.

If the sampling frequency is set much too high, decimation can be applied to reduce the sampling frequency. However, data must be low-pass filtered, first, in order to prevent possible aliasing phenomena resulting from down-sampling. The cut-off frequency of the low-pass filter should be no larger than 0.8 times the final sampling frequency after decimation.

Independently of the motivations, when data are filtered, the same filter and filtering parameters must be applied to all measurement channels in order to prevent possible distortions in mode shape estimation.

While the sampling frequency limits the maximum frequency that can be identified, the total record length has an impact on the accuracy of modal parameter estimates. If preliminary estimates of the natural frequency and damping ratio of the fundamental mode of the structure under test are available, the minimum record length can be estimated as follows [1]:

$$T_{min} = \frac{n_d}{\pi \cdot \xi_1} \cdot T_1 \tag{2}$$

where T_{min} is the required minimum duration associated with a given level of accuracy, controlled by the number n_d of averages in PSD estimation (this value can be set equal to 100 for accurate estimation), and T_1 and ξ_1 are the natural period and damping ratio of the fundamental mode, respectively.

In common applications, a record length of about one hour largely fits this requirement. It is worth noting that longer durations should be cautiously considered, because the stationarity assumption for the structure may be jeopardized.

Special attention should be paid to the nature of the input, even if it is in principle non-controllable and immeasurable. The traditional assumption of structure excited by white noise implies that the input spectrum is constant and, as a consequence, all modes are equally excited, so that the output spectrum contains full information about the structure. However, this is rarely the case, since the excitation has a spectral distribution of its own, and that is often broadband but it might also include spurious frequency components associated with particular excitations. Modes are, therefore, weighted by the spectral distribution of the input, and the properties of the input as well as the structure are observed in the response. If spurious dominant frequencies associated with the excitation are present, these should be identified and excluded from the results set. The simplest method to identify spurious harmonics consists in inspecting the spectrum of the signal at high resolution: spurious harmonics, in fact, usually appear as sharp peaks. This simple approach is sufficient in a majority of civil engineering applications. However, more refined methods are also available in the literature. Please, refer to [1, 2] and the references therein for more details.

About the nature of the input, in addition to the above it is worth considering that additional artificial excitation can sometimes be applied to enhance the signal-to-noise ratio of the measured signals. The additional excitation should be selected in a way that it does not hide structural modes: in particular, it should not hamper the identification of closely spaced modes. This is the case, for instance, when only one dominant input is present, or in the presence of multiple fully correlated inputs, or when free decay data are used for output-only modal identification. In the latter case, a possible countermeasure consists in adopting multiple sets of initial conditions. In a similar way, output-only modal parameter estimation based on heavily non-stationary data (such as the structural response associated with earthquake loading) is not recommended.

The main options for storage are database and log files. The most common file formats are .csv, .asc, .txt, .lvm, .tdms, .xls., UNV binary/ ASCII; native binary are also common options (see, for instance, .mat files). Some of the previously mentioned file formats are particularly attractive because they store data in compressed format, thus allowing to save storage space. In addition to the previously mentioned file formats, some companies have defined native file formats for their equipment/software, but they might require additional conversion tools to make data available in different file formats. While native formats can be accepted, it should be noted that conversion tools are not always available or they are available at an extra cost. Thus, selecting measurement equipment/software ensuring interoperability is recommended. In this case, metadata can be exploited to support file exchange: for instance, when ASCII files are used, the decimal separator symbol must be declared to avoid data misinterpretation.

5. PRE-PROCESSING

5.1. Data validation and pre-treatment

The collected data should be checked for validity and pre-processed in order to extract the modal parameters. Aspects that can be considered to assess the validity of data are:

- Duration of the record (Section 5.4);
- Presence of (heavy) transient signals;
- Relative amplitude;
- Missing data;
- Clipping due to an incorrect matching between sensor output and digitizer input, offset error, or inappropriate selection of the full-scale range of the sensors;
- Excessive measurement noise (yielding high noise floor that might hide structural resonances or seriously affect the signal-to-noise ratio);
- Excessive digital noise (due to an incorrect matching between sensor output and digitizer input);
- Noise spikes (due to defective connections or shielding).

Offsets and spurious trends are also sometimes present in the time series. If the mean value of the data is known to be zero (this is the case of structures subjected to null net acceleration, such as civil structures), the offset can be removed by subtracting the mean values to the corresponding time series. Trends in the data can be detected by visual inspection. In general, they may be physically meaningful if the signal has a time-varying mean value and the measurement system frequency range goes to DC. However, trends are very often spurious and they may occur for a number of reasons. In most cases, they are induced by temperature. Spurious trends lead to a magnification of the low frequency components in the auto-spectrum of the signal. In particular, the frequencies below $10/T_r$ are affected, where T_r is the total record length. These frequencies are typically well below the frequency range of interest. Thus, a correction of the time series for removal of spurious trends usually does not affect the analysis results but, on the contrary, it prevents a misinterpretation of the data. Two methods can be adopted to remove spurious trends from the datasets. Whenever low frequency information in the data has to be preserved down to the minimum frequency $1/T_r$, regression analysis represents the best method for removal of spurious trends. It consists in fitting a low-order polynomial to the data using least squares procedures. The values of the polynomial are subtracted afterwards from the time history. Fitting of polynomials of order larger than 3 is not recommended because they might remove actual low-frequency information in the data together with the spurious trend. If the low-frequency components below $10/T_r$ are not of interest, spurious trends can be removed by high-pass filtering. This is usually the case when the total time histories are divided into blocks for the computation of ensemble-averaged spectra, since the frequency resolution adopted in spectrum computation is typically larger than $10/T_r$.

Filtering is frequently applied to remove undesired frequency components; for instance, low-pass filters are frequently applied before decimation or to remove 50/60 Hz spurious harmonics from power lines, power supply ripple or electromagnetic fields, while high-pass filters are applied to remove frequencies close to DC such as those due to offset and spurious trends. When filtering the data, it is important to take into account the errors on amplitude and phase induced by filters. However, if the same filtering operation is applied to all measurement channels in the dataset, it does not negatively affect the estimation of the mode shapes. In any case, filtering should be applied after inspection of the raw time series for validation purposes: in fact, filtering can jeopardize the data validation phase hiding some evident defects, such as noise spikes or excessive digital noise, and preventing the application of the appropriate countermeasures (cutting time series, checking connections and shields, checking the coupling between sensors and data acquisition system, to name a few).

5.2. Computation of PSD and correlation functions

Correlation functions and PSD functions play a primary role in output-only modal identification. In fact, under the assumption of stationary and random response of the structure, the second order statistics of the response carry all the physical information.

If modal parameter estimation is carried out in the time domain, correlation functions must be estimated. Auto- and cross-correlation functions can be either directly or indirectly estimated.

Direct estimation is carried out according to the following formulas (valid for zero mean, uniformly sampled, stationary data):

$$\hat{R}_{xx}(r \cdot \Delta t) = \frac{1}{N-r} \cdot \sum_{n=1}^{N-r} x_{n+r} \cdot x_n \qquad r = 0,1,2,\dots,m \tag{3}$$

$$\hat{R}_{xy}(r \cdot \Delta t) = \frac{1}{N-r} \cdot \sum_{n=1}^{N-r} x_{n+r} \cdot y_n \qquad r = 0,1,2,\dots,m \tag{4}$$

while indirect estimation is based on the Inverse Fourier Transform of PSD functions.

If modal parameter estimation is carried out in the frequency domain, one-sided auto- and cross-PSD functions must be computed. PSDs can be represented in different ways: real part and imaginary part as a function of frequency, or magnitude and phase as a function of frequency. The latter representation is more commonly adopted. In any case, assembling and manipulating the PSD matrix requires a complex valued representation (the PSD matrix is a Hermitian matrix).

In the computation of PSDs, windowing must be applied to avoid leakage. Hanning window is typically applied to this aim. Different windows can be applied if appropriately motivated.

When the Welch procedure is applied for PSD estimation, linear averaging is recommended. Averaging is the noise reduction strategy typically adopted in frequency domain methods. It allows reducing the random error, which is theoretically inversely proportional to the square root of the number of averages in the computation of PSDs. A large number of averages ($n_d \approx 100$; see also Section 5.4) is recommended. It implies long records (Section 5.4) in order to avoid the introduction of bias errors due to the poor frequency resolution. The number of averages can be increased by partial overlap. The maximum recommended overlap is 66%.

6. OUTPUT-ONLY MODAL PARAMETER ESTIMATION

OMA methods are usually classified according to different criteria pointing out specific features common to different analysis methods. Thus, evaluating the main features of a given OMA method represents a fundamental step towards the appropriate selection of the modal parameter estimation techniques to apply.

A classical distinction is based on the domain of implementation. Time domain OMA methods extract the modal parameters from the analysis of response time histories or correlation functions, while frequency domain OMA methods rely on PSD functions. This distinction, which may appear artificial because it just refers to different representations of the same signal, actually holds a significant information about the noise rejection mechanism, which is different in the two cases. Moreover, different issues characterize model fitting in parametric methods depending on the domain (time or frequency) they work in.

The previous classification introduces another relevant distinction between parametric and non-parametric methods, depending if a model is fitted to data, or not. Parametric methods are more complex and computational demanding with respect to the non-parametric ones but they usually provide more accurate estimates. Non-parametric techniques, on the other hand, can be exploited during field tests to get a quick insight of test results.

Another relevant distinction is between low order and high order methods. In fact, the number of identifiable modes is limited by the number of measurement channels in low order methods, while high order methods do not suffer this limitation.

Depending on the assumption about the number of modes determining the structural response in a given bandwidth, OMA methods can be classified as SDOF or MDOF methods. In the presence of closely spaced or even coincident modes, MDOF methods are the only option.

Finally, OMA methods can be classified as one-stage or two-stage methods depending if natural frequencies, damping ratios and mode shapes are estimated at once or not. Two-stage methods may require a few iterations for mode selection.

Table 1 summarizes some of the most common OMA methods with their relevant characteristics [1, 2]. The table can guide the user towards the selection of the most appropriate method for the application.

It is worth pointing out that several other OMA methods exist and others might be developed in the future. Since method selection is up to the technician, any OMA method can be applied provided that its reliability and accuracy are demonstrated in the scientific literature, and taking into account possible limitations dictated by its inherent features and classification.

In practical applications, using at least two distinct techniques (for instance, a time domain parametric method, and a frequency domain non parametric method) is warmly recommended to validate the results from the two methods against each other. However, the number and type of OMA methods to apply also depend on the complexity of the application: the simplest possible case is where only a few well-separated modes are to be estimated; the most difficult case concerns the identification of a large number of modes, many of them closely spaced. The latter identification task can only be successfully performed if several different identification approaches are applied.

Table 1. *Main characteristics of well-established OMA techniques*

Name	Abbreviation	Domain	Parametric	Low-order	Two-stage	Closely spaced modes
Ibrahim time domain	ITD	Time Domain	Yes	Yes	No	In recent version
(Poly-reference) Least Square Complex Exponential	p-LSCE	Time Domain	Yes	No	Yes	In the poly-reference version
Eigensystem Realization Algorithm	ERA	Time Domain	Yes	No	No	Yes
Stochastic subspace Identification (either covariance driven or data driven)	SSI	Time domain	Yes	No	No	Yes
SOBI	SOBI	Time domain	No	Yes	Yes	No nearly repeated modes
Frequency Domain Decomposition	FDD	Frequency domain	No	No	No	Yes
(Poly-reference) Least Square Complex Frequency	p-LSCF	Frequency domain	Yes	No	Yes	In the poly-reference version

When applying parametric OMA methods, the influence of analysis parameters on modal identification results should be considered. For instance, with reference to SSI, it is well known that the number of block rows plays a primary role in the determination of the order of the system and in the discrimination between physical and spurious modes by the stabilization diagram [9]. A number of inequalities have been reported in the literature to set a lower bound for the number of block rows. However, they do not suggest optimal settings of the number of block rows, which can be determined by a sensitivity analysis where the maximum model order is kept fixed, and the number of block rows varies. The quality of the resulting stabilization diagram is inspected and the one yielding the minimum variance of modal parameter estimates at varying model order is taken as reference [10]. It is also worth noting that, if the number of block rows is set much too high, the mathematical poles are pushed towards the alignments of physical poles, causing a bias in modal parameter estimates. Thus, the optimal value of the number of block rows comes from a trade-off between the opposite needs of noise rejection (which requires to increase the number of block rows) and of obtaining unbiased estimates (which requires to limit its value).

If very small or very large channel counts are used, adjusting the number of signals used for OMA might be considered. In case of very small channel counts, the measured signals can be time shifted and stacked. In case of very large channels counts the measured signals might be condensed by PCA of the covariance matrix of measured data. To this aim, the SVD of the covariance matrix is computed, first, and only the left singular vectors associated with the largest singular values are retained. The condensed responses are finally obtained by pre-multiplying the measurement dataset by the transpose of the matrix of the retained singular vectors.

7. DAMPING RATIO ESTIMATION

The determination of modal damping ratios from ambient vibration measurements is always associated with uncertainties that are much larger than those associated with the estimation of natural frequencies and mode shapes. This is partially due to limitations of the identification algorithms, and partially due to the influence of the structural response amplitude (normally higher amplitudes trigger additional mechanisms of energy dissipation) and of the environmental conditions (e.g. wind speed) on modal damping ratios.

Since damping is influenced by factors that are impossible to control, ambient vibration tests of the same structure performed under different operating scenarios might deliver very discrepant modal damping estimates. However, OMA has the great advantage of permitting the evaluation of damping in diverse operating conditions and in this way permits the characterization of the modal damping variation with the influencing factors that are measurable.

Damping ratio estimation follows different procedures in time domain and frequency domain.

The simplest method for damping estimation in the frequency domain is the half-power bandwidth method [11]. However, the resulting estimates show limited accuracy because they are heavily influenced by the resolution of the spectra, type of applied window, the noise observed around the peak, and possible neighbouring peaks.

The EFDD method yields damping estimates characterized by higher accuracy because it carries out a preliminary separation of the modal responses based on the evaluation of the MAC (Section 10) between the singular vector at the peak and those at neighbouring frequencies. Once the modal response of a given mode is isolated, the corresponding approximate auto-spectrum is converted to the time domain, and damping ratio is estimated from the corresponding auto-correlation function by fitting the exponential amplitude decay.

The effect of frequency resolution on modal damping ratios estimated by the EFDD method has been extensively investigated in the literature, showing that the damping ratio estimates for all modes decrease when the frequency resolution improves, and they converge for a frequency resolution equal to 0.01 Hz or better. Moreover, the bias in damping estimation is kept low by inverse Fourier transforming the identified SDOF Bell functions and by fitting the data related only to the first few cycles of the obtained approximate SDOF correlation functions for the considered modes. Particular attention is needed in the case of closely spaced modes, when damping estimates by EFDD might be inaccurate. In fact, partial identification of SDOF Bell functions, beating phenomena and errors due to windowing can significantly bias the estimates.

When parametric OMA methods are applied, the damping ratio estimate is directly obtained together with the natural frequency. When using SSI, the modal parameter estimates, including the damping ratio, are unbiased. The damping ratio estimates (like the other modal parameters) are sensitive to the selected parameters for the method and to the order of the adopted model. In time domain, the maximum time lag of the correlations can be selected to ensure that these contain a number of cycles of the relevant structure modes varying from 2 to 10. A minimum number is needed to characterize the decay, but too long correlations will contain smaller amplitudes more sensitive to noise. As an alternative, a sensitivity analysis can be carried out to take into account the effect of the number of block rows on the modal estimates (Section 7).

Taking into account the previous considerations, the application of alternative methods with diverse input parameters is recommended in order to increase the confidence on modal damping estimates. Additional recommendations can be given to deal with specific cases. If the damping is significantly influenced by viscoelastic effects, special care should be taken to investigate the influence of temperature and other operating conditions known to influence viscoelasticity. If the damping is heavily influenced by non-linear effects such as friction, the amplitude dependency of damping estimates should be investigated and documented. In cases of very small (smaller than 0.5%) and very high damping (larger than 5%), special care should be taken to use identification techniques that are well suited for the case.

8. MODE SHAPE ANALYSIS AND NORMALIZATION

Mode shape estimates obtained from OMA methods are, with a few exceptions, in the form of complex eigenvectors. These must be inspected to assess if they represent normal modes, characterized by nearly zero imaginary component of modal displacements, or they are actual complex modes. Complex modes are often obtained as a result of poor signal-to-noise ratio, but they can also originate from physical reasons, such as gyroscopic effects, aerodynamic effects and non-linearities, non-proportional damping. When noise is the cause of complex mode shapes, the degree of complexity is usually moderate. The simplest method to assess modal complexity is based on the inspection of the Complexity Plots.

Complex-to-real conversion is often required when experimental mode shapes are going to be compared with those obtained from numerical models, which are typically real-valued. In the presence of little or moderate complexity, as in the case of noise effects, a complex-to-real conversion of mode shapes can be carried out with negligible errors.

Mode shape estimates obtained from OMA methods are unscaled or, in other words, they are not mass-normalized. The most common types of normalization of experimental mode shapes are:

- Normalization to the unit length of the mode shape vector (length scaling);
- Normalization to a component (usually the largest component) equal to unity (DOF scaling);
- Mass normalization (or normalization to the mass matrix of the system).

The first normalization is obtained by pre-multiplying each mode shape vector for a constant equal to the inverse of its length. Normalization to the largest modal displacement is obtained by looking for the component of the (complex) experimental eigenvector characterized by the largest modulus, dividing all modal displacements by this value, and carrying out the complex-to-real conversion.

Mass normalized mode shapes must be known in applications where a frequency response matrix (or the impulse response function) needs to be assembled from the modal parameters. However, the input being unknown in OMA, mass normalized mode shapes can only be obtained by applying specific approaches for the estimation of the scaling factor. The mass-normalized $\boldsymbol{\phi}_{\boldsymbol{k}}$ and the unscaled mode shape $\boldsymbol{\psi}_{\boldsymbol{k}}$ are indeed related each other by the expression:

$$\boldsymbol{\phi}_{\boldsymbol{k}} = \alpha_k \, \boldsymbol{\psi}_{\boldsymbol{k}} \qquad (5)$$

where α_k is known as scaling factor and it is related to the modal mass m_k by:

$$\alpha_k = \frac{1}{\sqrt{m_k}} \tag{6}$$

The modal mass and the corresponding scaling factor can be estimated by the so-called "mass change method". This method consists of perturbing the structure attaching masses to it at locations where the mode shapes of the unmodified structure are known, and then repeating the modal testing on the perturbed structure. The modal masses are estimated using the modal parameters of both the unperturbed and the perturbed systems, and the known mass modifications. A simple expression to compute the modal mass of the k-th mode is [12]:

$$m_k = \frac{\boldsymbol{\psi}_{\boldsymbol{uk}}^{\boldsymbol{T}} \cdot \mathbf{\Delta M} \cdot \boldsymbol{\psi}_{\boldsymbol{pk}} \cdot \omega_{pk}^2}{\left(\omega_{uk}^2 - \omega_{pk}^2\right) \cdot p_{kk}} \tag{7}$$

where the subscripts $_u$ and $_p$ denote the unperturbed and perturbed structure, respectively, ω_{uk} and ω_{pk} the corresponding natural frequencies, $\boldsymbol{\psi}_{\boldsymbol{uk}}$ and $\boldsymbol{\psi}_{\boldsymbol{pk}}$ the associated mode shapes, and $\mathbf{\Delta M}$ the mass change matrix; p_{kk} is the k-th diagonal entry of the matrix $\boldsymbol{P}$ given by:

$$\boldsymbol{P} = \boldsymbol{\Psi}_{\boldsymbol{u}}^{\boldsymbol{-1}} \boldsymbol{\Psi}_{\boldsymbol{p}} \tag{8}$$

where $\boldsymbol{\Psi}_{\boldsymbol{u}}$ and $\boldsymbol{\Psi}_{\boldsymbol{p}}$ are the mode shape matrices of the unperturbed and perturbed structure, respectively (mode shape estimates are in columns). The number of measured DOFs and the number of identified modes are rarely the same, so $\boldsymbol{P}$ can be obtained as:

$$\boldsymbol{P} \approx \boldsymbol{\Psi}_{\boldsymbol{u}}^{+} \boldsymbol{\Psi}_{\boldsymbol{p}} \tag{9}$$

where the superscript $^+$ denotes pseudoinverse. The technique is usually applied by using lumped masses, in which case $\mathbf{\Delta M}$ is a diagonal matrix**.**

The magnitude, number and location of the masses used to perturb the structure must be carefully defined before applying this technique. An optimum strategy maximizes the frequency shift and, simultaneously, minimizes the changes in mode shapes. The frequency shift is maximized when the term $\boldsymbol{\psi}^{\boldsymbol{T}} \boldsymbol{\Delta M \psi}$ is maximum. The changes in mode shapes are minimized by proportional (to the mass matrix of the structure) and small mass changes [13]. It is worth pointing out that the accuracy of the mass change method mainly depends on the frequency shift between the unperturbed and the perturbed systems [13]. This implies rather large mass changes to allow for a reasonably frequency ratio and good modal parameter identification, in order to keep the relative uncertainty of the frequency shift down to a reasonable value. The following equation:

$$\varDelta\omega(\%) \approx \frac{\varDelta m(\%)}{2} \tag{10}$$

can be used to estimate the magnitude of the added masses. A minimum frequency shift $\varDelta\omega = 2.5\%$ is recommended for each mode. Eq. (10) relates the frequency shift $\varDelta\omega$ with the change of the modal mass given by:

$$\varDelta m = \frac{\boldsymbol{\psi}^{\boldsymbol{T}} \boldsymbol{\Delta M}\, \boldsymbol{\psi}}{\boldsymbol{\psi}^{\boldsymbol{T}} \boldsymbol{M}\, \boldsymbol{\psi}} \tag{11}$$

where $\boldsymbol{M}$ and $\mathbf{\Delta M}$ are the mass matrix of the system and the mass change matrix, respectively.
The number of added masses depends on the number of modes to be simultaneously estimated. For each mode, the number of masses should be equal or higher than the number of extrema of the mode shape.
About the location of the added masses, those located at DOFs characterized by the largest magnitude of modal displacements contribute the most to the frequency shift, whereas there is no contribution from masses located at nodal positions. Thus, the best locations for the masses, in order to modify the natural frequencies, are at DOFs characterized by the largest magnitude of modal displacements.
When modal masses are simultaneously computed for several modes, it is often impossible to optimize the mass location for all the modes. A possible strategy to overcome this drawback consists in performing several modal tests by changing the positions of the added masses.
As an alternative to the mass change method, the mass matrix of a FE model of the tested can be used to estimate the scaling. This approach is extensively illustrated in [14].
OMAH [15] is another technique that can be used to obtain a scaled modal model. It is based on applying several harmonic forces to the structure, to obtain some frequency response values that are used for the scaling. OMAH has some benefits over the previously described methods for scaling:

- the scaling is based on actual measurements of known forces applied to the structure;
- the accuracy of the scaling may be immediately assessed using the measured responses due to the harmonic excitation;
- possible nonlinearity of the structure may be assessed by applying varying force levels.

OMAH should be applied immediately after a regular OMA test to obtain the modal scaling; OMA and OMAH test must have the same sensor layout. The OMA should precede the OMAH test, so that the latter can take advantage of the knowledge of the mode shapes that will allow to choose the most appropriate DOFs to apply the (usually very small) harmonic excitation. After having selected the DOFs for input application, a shaker is used to apply the harmonic force at each selected DOF one by one. Measuring the response to the applied harmonic force for some time, the FRF values from the location of the force to the measured responses can be determined at the considered frequency. The process is repeated at several frequencies. The minimum number of tests should equal the number of modes plus two. This allows to calculate the modal scaling for all modes, plus the residual terms to account for the effect of modes above and below the frequencies of the OMA modes.

9. VALIDATION OF RESULTS AND CORRELATION

Model correlation techniques allows to compare two different models, which can be:

- two numerical models,
- a numerical model and an experimental model,
- two experimental models.

Model correlation plays a key role in experimental modal parameter identification as well as in validation and updating of numerical models (see also Section 12.1).

Although many correlation methods have been proposed in the literature, by far the most widely used techniques are the NRFD, and the MAC, which compares a set of mode shapes. Thus, NRFD can be referred to as an eigenvalue-based criterion whereas MAC as an eigenvector-based criterion. The NRFD compares two sets of natural frequencies associated with two models (either experimental or numerical). The NRFD corresponding to the j-th natural frequency of two models A and B can be computed as follows:

$$NRFD_j = \frac{\left|f_{Bj} - f_{Aj}\right|}{f_{Aj}} \qquad (12)$$

where f_{Bj} and f_{Aj} indicate the j-th natural frequency of models A and B, respectively, and model A is assumed as reference. When using this technique, a previous mode pairing is mandatory.

The MAC between two mode shape vectors, $\boldsymbol{\phi}_{\boldsymbol{Bi}}$ and $\boldsymbol{\phi}_{\boldsymbol{Aj}}$ (for model B and A, respectively), is given by:

$$MAC(\boldsymbol{\phi}_{Bi},\boldsymbol{\phi}_{Aj}) = \frac{\left|\boldsymbol{\phi}_{Bi}^{T}\cdot\boldsymbol{\phi}_{Aj}\right|^{2}}{(\boldsymbol{\phi}_{Bi}^{T}\cdot\boldsymbol{\phi}_{Bi})(\boldsymbol{\phi}_{Aj}^{T}\cdot\boldsymbol{\phi}_{Aj})} \tag{13}$$

where the superscript ^{T} denotes transpose. MAC values range between 0 (meaning no consistent correspondence) and 1 (consistent correspondence). In the practice, good correlation is associated with MAC values between 0.9 and 1, while MAC values lower than 0.7 indicate poor correlation.

If the vectors under comparison are complex-valued, the following expression is used to compute the MAC:

$$MAC(\boldsymbol{\phi}_{Bi},\boldsymbol{\phi}_{Aj}) = \frac{\left|\boldsymbol{\phi}_{Bi}^{H}\cdot\boldsymbol{\phi}_{Aj}\right|^{2}}{(\boldsymbol{\phi}_{Bi}^{H}\cdot\boldsymbol{\phi}_{Bi})(\boldsymbol{\phi}_{Aj}^{H}\cdot\boldsymbol{\phi}_{Aj})} \tag{14}$$

where the superscript ^{H} denotes complex conjugate.

The MAC values obtained by comparing two sets of vectors can be reported in matrix form, and the resulting MAC matrix can be represented in different formats: table, 2D plot, 3D plot.

Particular attention should be paid to closely spaced modes. As a rule of thumbs, two modes with natural frequencies ω_1 and ω_2, and frequency distance $\Delta\omega = \omega_2 - \omega_1$ can be considered closely spaced if:

$$\frac{\Delta\omega}{\omega} < \frac{1}{1000} \tag{15}$$

where $\omega \approx \omega_1 \approx \omega_2$.

Closely spaced modes are highly sensitive to small mass and stiffness perturbations of the system and they mainly rotate in their subspace, so low values of MAC can be obtained because of this rotation. As a result, only the subspace spanned by the mode shapes is important. A method to maximize the MAC correlation is to rotate the mode shapes in their subspace before the MAC calculation. In any case, it is worth noting that the mode shapes are orthogonal with respect to the mass and stiffness matrices, but they are not orthogonal to each other, so the MAC should be considered an approximation of orthogonality rather than a rigorous orthogonality check.

MAC can be exploited for mode pairing. If mode shapes are correctly paired and a good correlation exists between the mode shapes of models A and B, the diagonal entries of the MAC matrix will be close to 1 and the off-diagonal entries close to zero.

When a set of mode shapes are compared with themselves, the so-called AutoMAC is computed. The AutoMAC matrix is symmetric with values equal to one along the main diagonal. Large off-diagonal terms are frequently indicators of spatial aliasing or spurious modes included into the set of identified physical modes. When spatial aliasing is present some modes look similar due to the insufficient amount of information in the mode shapes, which indicates that not enough DOFs were measured to uniquely identify the individual modes. Thus, the AutoMAC is a good tool to check the effectiveness of sensor layout.

When two sets of experimental mode shapes for the same structure obtained from two different OMA methods are compared, the CrossMAC matrix is computed. This can be useful to assess the reliability of experimental results.

10. TEST REPORT

The final test report is expected to cover all relevant aspects of OMA tests by providing a comprehensive description of:

- The structure under test;
- Objectives of the test;
- Characteristics of the measurement equipment;
- Sensor layout and installation;
- Test execution;
- Data validation and pre-treatment;
- Modal parameter estimation methods and results;
- Validation checks and conclusions.

In general terms, all data and information useful to ensure repeatability and reproducibility of the test should be included in the test report. The present section provides an extensive, but not necessarily comprehensive, list of relevant data, information and aspects worthy of attention for the sake of preparation of the final test report.

About the structure under test, the document should provide relevant information such as typology, age, geometry, supports, constraints, joints, and any other structural detail that might have an influence on the dynamic behavior, including possible damage.

Motivations for the execution of the OMA test and general as well as specific objectives of the test should be declared, and how they affect the selection of measurement equipment and sensor layout as well as test execution should be discussed.

Relevant characteristics of the measurement equipment must be reported. Technical datasheets of sensors and data acquisition system should be provided as an attachment, together with relevant documentation pertaining to calibration, if required or appropriate. The selection of the measurement equipment must be adequately motivated, paying particular attention to the expected vibration levels and frequency range of interest.

Criteria and motivations under the definition of the sensor layout must be clearly reported. Sensor layout should be provided by graphic illustration, with the measured DOFs identified by letters or numbers or a combination of the two, if appropriate. The graphical representation of sensor layout must precisely indicate the position of each sensor, providing relative distances as well as distances from an absolute reference. In the case of multi-layout tests, locations and directions of the reference sensors, and of the roving sensors in each test, must be clearly indicated. If test results will be used for model validation/updating, the correspondence between sensor positions and nodes of the FE model must be evaluated. Sensor installation must be accurately described and documented by photos of the sensors in the field. Additional photos useful to identify and verify nomenclature, positions and orientations of the sensors should be included in the test report. Mounting method and the motivations behind its selection have to be reported, too (see also Section 5.3). Additional installation information concerns the length of the cables, their path (also for the evaluation of possible noise sources), type of cables, and so on. In the case of wireless communication, type of network, accuracy of synchronization, limit distances and any other parameter that might affect the quality of measurements should be reported and discussed.

The illustration of test execution should report relevant data acquisition parameters (i.e., sampling frequency, record duration, and so on) and appropriate motivations for their setting. In addition, it should report a description of the environmental and operational conditions at the time of testing. Quantitative measurements of relevant variables that might affect the test results (i.e., temperature, and so on) should be reported, whenever possible.

A discussion about the validity of data should explicitly mention possible problems encountered during the test; motivations under measurement errors (for instance, defective connectors, electromagnetic interference, and so on) and the possible countermeasures adopted in view of modal parameter estimation must be explicitly reported and discussed. The applied procedures of data pre-treatment must be illustrated in their most relevant aspects, and how they affect modal parameter estimation should be discussed. Filtering, decimation, and windowing operations (Section 6) must be accurately documented in the report.

The OMA techniques used for modal parameter estimation must be well-established and well-documented in the literature. Details about the OMA procedure(s) used for modal parameter estimation must be included in the technical report together with the motivations for their application (for instance, closely spaced modes are expected, or damping estimation is needed) and the adopted settings for the analysis parameters. Whenever stabilization diagrams are used, stabilization criteria must be specified so that the results can be reproduced. The adopted OMA methods should be able to identify at least the natural frequencies and the associated mode shapes of the structure under test. If damping estimates are required, suitable techniques should be used (see also Section 7 and Section 8).

The identified modal parameters should be reported at least in the form of tables. Possible sources of random and bias errors should be identified, and a quantification of those errors should be provided whenever possible. Random errors can be estimated by repeated testing. Bias errors can be investigated using simulations or by changing some of the basic user choices. Whenever simulations are used to investigate bias errors, those must be separately documented. If damping is of interest for the OMA investigation, care should be taken to illustrate and document the uncertainty of the damping ratio estimates, with special focus on possible bias sources (Section 7 and Section 8).

In addition to reporting the numerical values of modal displacements at the measured DOFs in the form of a table and a qualitative description of the nature of the mode (bending mode, torsion mode, and so on), complexity plots as well as static display of the identified mode shapes should be included in the test report. Indeed, the experimentally identified mode shapes are usually plotted in static or animated form. The static display provides a picture of the mode shape, eventually superimposed to the undeformed configuration of the structure. This is the representation format adopted for test reports. However, visual inspection of complex mode shapes by static plots can be misleading. Inspection of animated mode shapes is therefore recommended whenever possible to overcome the limitations of static display. Animated plots, in fact, simulate the swing of the structure according to the selected mode shape, so they can effectively represent also complex modes. Whenever complex modes are identified, since animated mode shapes can be visually inspected on screen but cannot be included in the test report, static display at different instants should be reported.

Visual inspection of the identified mode shapes represents one of the typical validation checks, so its outcomes should be discussed in the test report. If appropriate, the test report can include a discussion about the motivation for rejecting possible spurious modes based on the inspection of the associated mode shapes.

Validation of the experimental results must include comparisons of the modal parameter estimates provided by different OMA methods, possibly a time domain method and a frequency domain method. Comparisons are usually expressed in terms of NRFD and CrossMAC.

The test report should also discuss the effectiveness of sensor layout in distinguishing the identified modes by providing the AutoMAC matrix in the form of either numerical values or plot. Specific comments should be added about the identified mode shapes whenever the associated complexity plots denote the presence of non-negligible imaginary components. In particular, it is recommended to ascertain if complex-valued mode shapes are due to measurement noise, possible spurious pole selection, or actual non-proportional damping.

Finally, the obtained OMA results should be compared with those of previous or independently carried out OMA tests, if available, discussing the influence of operational conditions, if appropriate. Correlation with results of numerical models, even if provided by third-parties, can be included in the test report, if required, in a specific section and discussing the quality of the correlation between the experimental and numerical modal parameters as well as the possible reasons behind the observed discrepancies.

11. TYPICAL APPLICATIONS

11.1. Finite Element model updating

The experimentally estimated modal parameters are frequently used as input or reference for a number of applications, including model updating [16]. The modal parameter estimates provided by FE models are, indeed, affected by inaccuracies due to discretization and modeling assumptions. As a result, the numerical model is typically not representative of the actual dynamic behavior of the structure, and a correction is needed. The correlation between experimental and numerical modal parameter estimates is, therefore, evaluated and used as a metric to refine the FE model. The updated model can be, in turn, used to obtain more reliable predictions of the structural response to dynamic loadings, or for damage detection purposes in the context of SHM applications (see, for instance, [17]).

FE model updating methods are traditionally classified into direct and indirect (iterative) methods. The formers proceed by adjusting individual elements in the mass or stiffness matrices of the structure. However, they might result in unphysical solutions, so they have been progressively abandoned in favor of indirect methods. Model updating can be further classified into manual or automated. In manual model updating a trial-and-error approach is adopted to tune a set of parameters selected according to engineering judgment. Manual tuning is usually applied when the initial FE model is already a close representation of the actual structure. In the automated approach, model updating is achieved by iterative minimization of a given objective function measuring the dissimilarity between corresponding experimental and numerical modal properties. Different optimization techniques can be applied to this aim.

When iterative optimization procedures are applied, the FE model is recursively analyzed in order to get the value of the objective function at each iteration; alternatively, a mathematical function approximating its response when varying selected updating parameters can be introduced into the objective function. This is the case, for instance, of the application of surrogate models for the solution of the model updating problem. Examples of surrogate models are the response surface method [18], or the Douglas-Reid method [19]. An extensive illustration of model updating methods is out of the scope of the present guidelines. The interested reader can refer to the literature for more details.

11.2. Tensile load estimation

Bridge cables, diagonal braces of trusses, tie-rods of arches and vaults in ancient masonry buildings are examples of axially loaded one-dimensional structural members frequently encountered in civil structures. The indirect evaluation of the axial load is another possible application of the experimentally identified modal parameters. It has an impact also in the context of SHM applications, because of the opportunity to use in-situ measurements of the axial load to quantitatively assess the health state and performance of the monitored structure [20]. Anomalous variations of the tensile load can, indeed, reveal structural degradation and, at the same time, they affect the internal force distribution. The significant applicative perspectives motivated the intense research efforts in recent years to develop methodologies for the evaluation of the axial force from experimental modal parameter estimates.

Depending on the characteristics of the axially loaded structural member, a number of methods have been developed under different assumptions for the indirect estimation of the axial load from the experimental modal parameters (natural frequencies and, in some cases, mode shapes) of the investigated element. They can be classified depending on the number of considered modes (single mode vs. multiple modes) and the assumptions on boundary conditions (fixed or hinged end supports vs. unknown boundary conditions), shear deformation, and rotary inertia (Euler-Bernoulli vs. Timoshenko beam model). In any case, the estimation of the tensile load from experimentally determined modal properties requires the solution of an inverse problem. In some cases, closed form solutions are available [21]; if this is not the case or correction factors [20] cannot be applied, iterative approaches are usually employed to solve the problem. The interested reader can refer to the literature for more details (see, for instance, [1, 22, 23]).

11.3. Structural Health Monitoring

Vibration-based SHM of civil structures is one of the most popular applications of OMA. It is a very active research field, and extensive surveys and dedicated books are available in the literature (see, for instance, [24]).

The monitoring process consists in the observation of the structural response over long periods of time, and in the automatic extraction of damage sensitive features from the collected data in order to assess the health conditions of the structure itself. In particular, modal based damage detection is based on the assumption that damage affects the physical properties of the structure (mass, stiffness and damping), so it is theoretically possible to identify it from the analysis of the variations of the modal parameters over time. However, the accuracy of damage identification is often jeopardized by a certain sensitivity of the modal properties to environmental and operational variables. As a result, automated OMA procedures as well as methodologies for the compensation of the influence of environmental/operational factors on the estimated modal properties are needed for a successful implementation of modal-based SHM strategies. Their extensive illustration is out of the scope of the present guidelines, so only basic criteria for the classification and selection of automated OMA procedures for SHM applications are mentioned here.

The research on automation of OMA procedures is relatively recent, and a wide consensus about the best strategies for the automatic estimation of modal properties from the measured structural response has not been achieved, yet. Nevertheless, several automated or semi-automated OMA procedures have been developed in the last decade and they are currently available for the applications. Thus, a basic understanding of the principles under their development is needed in view of their rational selection for SHM applications.

Most of the automated OMA procedures represent an evolution of traditional (manual) OMA methods, since they rely on the same theoretical concepts. However, the development of automated OMA procedures is not a trivial task, since traditional OMA requires extensive interaction with a skilled analyst. When automated OMA is integrated within continuously operating SHM systems, reliability, accuracy, and computational efforts have to be carefully assessed, too.

Nowadays, a widely accepted classification is between automated and semi-automated OMA procedures. The formers estimate the modal parameters from a single dataset without any prior information about the dynamic properties of the structure under investigation; semi-automated procedures, on the contrary, require a set of reference modal parameters to operate. This set can come from either an automated or manual modal identification. In spite of their minor autonomy with respect to fully automated modal parameter identification methods, semi-automated procedures are often advantageous for applications requiring short response time and little computational efforts.

Additional classifications refer to the main characteristics of the OMA techniques underlying the development of the automated procedure (Section 7). However, those criteria might be less strict when the classification of automated OMA procedures is considered; for instance, with respect to the domain of implementation, it is possible to find algorithms that combine data processing steps typical of time domain as well as frequency domain OMA methods. Thus, rather than classifying the automated OMA procedures with respect to specific features, it is important to check if they are able to satisfy some basic requirements for their application in the context of SHM. In particular, automated OMA procedures should:

- provide accurate and precise modal parameter estimates, including damping;
- not rely on application-dependent parameters that have to be tuned by the user (the initial calibration could be inadequate to ensure a reliable tracking of the modal properties over time) or, alternatively, they should be characterized by proved robustness to follow the natural variability of modal parameter estimates due to environmental/operational effects as well as damage or degradation phenomena;
- be effective also in the presence of closely spaced modes;
- be robust to spurious harmonics and slight non-stationarities;
- be characterized by a high success rate (robustness with respect to problems of false and missed identification);
- include options for the control of response time.

The previous considerations remark that automation of OMA is currently a very active and rapidly evolving research topic, and a thorough and systematic discussion about automated OMA procedures is still to be developed. Nevertheless, significant progress is expected in the next years due to the primary role automated OMA plays in the development of SHM strategies for civil engineering applications.

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