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Operational Modal Analysis of Structures in Civil Engineering

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ABSTRACT

In civil engineering, operating Modal Analysis (OMA) has become a potent tool for assessing the dynamic properties of structures in real-world operating scenarios. This study provides an extensive overview of the latest developments and uses of OMA techniques in the field of civil engineering, with particular attention to the identification of modal parameters, the modal assurance criterion, and the reconstruction of mode shapes. The basic ideas behind OMA approaches are covered, including modal parameter estimate algorithms, signal processing strategies, and data collection techniques. OMA presents several obstacles, including structural nonlinearities, measurement noise, and environmental effects. These issues are discussed along with solutions. In addition, case examples demonstrating the effective application of OMA in civil engineering projects—such as vibration-based condition evaluation, damage detection, and structural health monitoring— are provided. The benefits of OMA over conventional modal analysis techniques are emphasized, especially its capacity to evaluate structures while they are in use without interfering with regular operations. To improve structural performance assessment and maintenance procedures, interdisciplinary cooperation and the integration of cutting-edge sensing technologies are crucial. Future directions and research paths in the field of OMA for civil engineering applications are finally described.

Keyword: ***OMA, Operational Modal Analysis, Transducer, Materials***

I. INTRODUCTION

It is a standard procedure to do experimental testing to learn more about the dynamic behavior of civil constructions. Specifically, it is possible to trace the experimental determination of the modal parameters back to the mid-1900s (Ewins 2011). Experimental Modal Analysis (EMA) determines those parameters from measurements of the applied force and the vibration response, assuming that the dynamic behavior of the structure can be expressed as a combination of modes. Each mode is characterized by a set of parameters (natural frequency, damping ratio, mode shape) whose values depend on geometry, material properties, and boundary conditions.

Over the last few decades, the concepts of system identification and experimental modal parameter estimate have yielded novel instruments for comprehending and managing vibrations, refining architectural designs, and evaluating the structural health and performance. The development of new high-performance materials and the growing complexity of structures have required powerful tools to support and validate the numerical analyses, even though the Finite Element (FE) method and the rapid advancement of computing technologies have made excellent analysis tools available to the technical community. In this context, the experimental identification of the modal properties undoubtedly aids engineers in gaining a deeper understanding of the structure's dynamic behavior and distinguishing between errors resulting from discretization and those arising from oversimplified or incorrect modeling assumptions. Furthermore, pressures stimulating the structure at resonance frequencies result in strong vibration responses that can cause pain or even damage since the vibration response is derived from the modes, which are intrinsic qualities of the structure. The evaluation of the structural integrity and performance can be aided by the regular determination of modal parameters and the study of their fluctuation.

Testing apparatus and data processing methods have advanced dramatically since EMA's founding. The discipline of EMA is presently well-established and has a strong theoretical foundation. Several books (Ewins 2000, Heylen et al. 2010, Maia et al. 2011) that have been widely accepted as references by the scientific and technical community provide a thorough demonstration of EMA procedures.

EMA has been used in a variety of engineering domains, including industrial machinery, civil engineering, automotive engineering, and aerospace engineering. Because of their size and limited frequency range, civil engineering structures provide more challenges for EMA approaches to identify the modal parameters. Applying quantifiable and controlled stimulation is sometimes a difficult process requiring bulky, costly equipment. Because of this, the field of civil engineers has recently concentrated on the advantages that Operational Modal Analysis (OMA) offers. OMA is a modal testing technique that enables experimental estimate of the structure's modal characteristics based only on vibration response data. The aim of OMA is to replace artificial stimulation with free and natural excitation caused by operating loads and ambient forces (wind, traffic, micro-tremors, etc.). Consequently, they are no longer regarded as disturbances but rather allow for the dynamic identification of enormous civil constructions. OMA is often referred to as ambient vibration modal identification or output-only modal analysis since it only necessitates measurements of the structure's dynamic response during operating circumstances when it is exposed to ambient stimulation.

1.1: Preliminary Concepts

To set some terminology and to understand the overall framework of application of the topics depicted in this book, a preliminary, brief discussion of signals and systems is undoubtedly helpful. The concepts of signals, systems, and structural dynamics that are described serve to identify the cultural backdrop that is necessary to begin the study of OMA. For further information and a more thorough examination of the notions described here, the interested reader can consult the literature (see, for example, Chopra 2010, Ewins 2010, Bendat and Piersol 2010).

Any physical quantity that varies in relation to one or more independent factors and is connected to relevant information is called a signal. An input signal is transformed into an output signal by a system. Important details about the system may be learned by mapping the response to a particular stimulus. For example, determining the dynamic properties of a structure may be achieved by analyzing its swinging (output signal) under wind load (input signal). Forward issues are the typical type of engineering challenges. For example, their goal is to estimate how a known system would react to a particular input. Inverse issues, on the other hand, are those in which the system attributes or the input are unknown, but the outcome is known. If the output signal is known (and some assumptions about the input are established), special emphasis is paid to identifying the features of the system.

Any unwanted signal overlaid on the signal of interest is referred to as noise. The signal-to-noise ratio (SNR), which is measured in dB and stated as follows, indicates how much noise is present in a signal:

$$SNR = 20\log_{S_a}(S_n)$$

whereas and A stand for, respectively, the signal and noise amplitudes (both stated in the same units). The signal of interest may become indiscriminate at low SNRs. Therefore, it's necessary to use the right data collecting techniques to reduce the amount of noise that always taints observations.

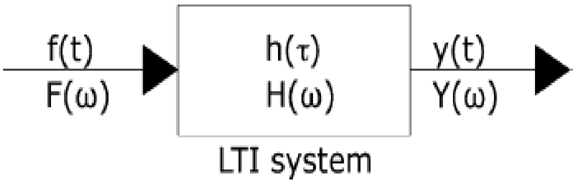


Figure No. 1 : LTI System

It is common practice to define an ideal constant-parameter linear system (sometimes called a linear time-invariant, or LTI, system; see Fig. 1.1) to explain the dynamic behavior of physical systems. If all a system's basic characteristics remain constant across time, it can be said to have constant parameters. Furthermore, if the response characteristics are additive and homogenous, it displays a linear mapping between input and output. Consequently, the system's reaction to a linear combination of inputs is equivalent to the system's response to everyone, independently examined input. The assumption of constant parameters holds true for a few physical systems that are encountered in practical applications. Its applicability, therefore, is contingent upon extending the time under consideration.

1.2: Fundamental Principles and Applications of OMA

This is the case, for example, with constructions that are continuously vibrated, when fatigue damage can alter the structure's stiffness. For the output-only modal testing, the time intervals of practical interest allow for the consideration of the structure as time invariant. For actual structures, the linearity assumption's validity is contingent upon both the structure's attributes and the size of the input. Large, applied loads on physical systems usually result in nonlinear response characteristics. Furthermore, the presence of a transition adds to the complexity of the issue because nonlinearities are frequently not linked to sudden changes in the response. To guarantee that high-quality information regarding closely spaced modes can be retrieved from the measured data, certain steps and functional tests are required. One way to accomplish this goal would be to make sure the data has an adequate quantity of independent information. It is demonstrated in Chapter 4 that the input PSD matrix and the structure's FRF matrix may be used to express the output power spectral density (PSD) matrix (4.12). Its rank, which indicates the number of independent rows or columns in the matrix, is therefore limited to the rank of each separate matrix that appears in the product. This suggests that if the rank of the input PSD matrix is one, then closely spaced modes cannot be predicted.

The true physical features of the structure may be partially concealed by rank deficiency across a narrow frequency range around the thought to be closely spaced modes (for example, by showing just one of the modes, or a mixture of the two modes). Thus, the ability to get high-quality data from modal testing is largely dependent on the appropriate design of the sensor arrangement and an early assessment of the sources of excitation operating on the structure under its operational circumstances. Several sensors enable the rank of the FRF matrix to be maximized, and many uncorrelated inputs guarantee the rank of the input PSD matrix to be maximized. Conversely, sensors positioned in nodes of mode shapes or numerous sensors measuring the same DOF (thus contributing no new independent information) restrict the rank of the FRF matrix; correlated inputs or input applied in a single spot, on the other hand, limit the rank of the input PSD matrix. In Chapter 3, several suggestions are provided for defining sensor layout for repeated typologies of civil constructions. Regarding the input, external loads like wind and traffic or moving loads acting on the structure cause the rank of the PSD matrix to be greater than 1.

Even with the variations in excitation, output-only modal testing follows the same three fundamental processes as traditional input-output testing:

- Testing preparation and execution: this phase includes defining the experimental setup (sensor layout, measurement chain, attachment of sensors, cable pathways, etc.) and data collecting settings (record length, sampling frequency, etc.).
- Data processing and modal parameter identification: this stage involves the estimation of the modal parameters, some signal processing operations (such as for the computation of correlation functions, PSD functions, random decrement functions, transmissibility functions, etc.), and the validation and pre-treatment (filtering, decimation, etc.) of the acquired data.
- verification of the estimated modal parameters.

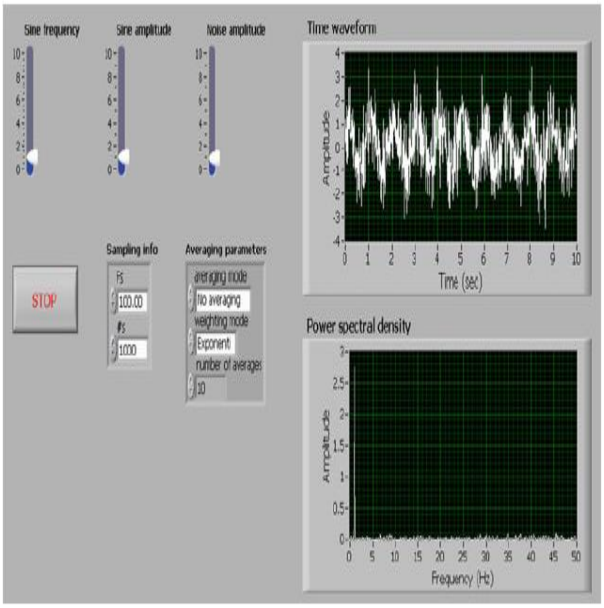
The estimation of the modal masses, or equivalently, the scaling factors of mode shapes, represents an application of modal parameter estimations that is somewhat connected to vibration based SHM and to intrinsic limits of OMA approaches. Operational modal testing yields only unscaled mode forms since the input is not quantified. Because of this, specialized methods have been created for the estimate of the scaling factors, based on the application of well-known structural alterations. Chapter 5 discusses this subject. Among other things, the calculation of the scaling factors enables the implementation of a certain class of damage detection algorithms (see, for example, Doubling et al. 2010, Pandey) and the reconstruction of the FRF matrix from the experimental findings.

II. A Platform for Measurement Execution and Data Processing

2.1 : Generalities

The user's background and ability level always have a role in the programming language chosen for software implementation. If one has access to sophisticated mathematics and data processing tools and can manage connection with measuring devices for data gathering, it is easy to implement the techniques and systems in the book using any programming language. This book suggests using LabVIEW, which was first created with the goal of combining measurement and data processing on a single platform, based on the authors' experience with the program. In addition to being incredibly strong and adaptable, it has a favorable learning curve that makes system and software development quick and simple.

Indeed, there are a lot of sophisticated features and analytical tools accessible, which enable connection with a lot of commercial equipment. Since LabVIEW is used as the common platform for system and software implementation in all of the suggested applications, an overview of pertinent features of programming in LabVIEW is provided in this section. It is evident that numerous platforms may be used for data processing and measurement execution; however, due to practical constraints, it is not feasible to offer tutorials for all programming languages. However, because the algorithms are universal, any alternative option for their implementation can be used, as long as the reader does the necessary translations between languages.



Fs 1000.00
#s 1000
averaging mode No averaging
weighting mode Exponent
number of averages 10

Figure No. 2 : Front Panel

Because LabVIEW applications mimic the look and feel of real instruments, including oscilloscopes and multimeters, they are also known as Virtual Instruments, or VIs. A vast array of tools for data collection, analysis, presentation, and archiving, as well as troubleshooting code, are included in LabVIEW (National Instruments 2005a). The creation of a user interface, or Front Panel (Fig. 1.2), with controls and indicators—the interactive input and output terminals of the VI, respectively—is necessary for programming in LabVIEW. A basic VI to examine a signal's fluctuations and spectra for varying component amplitudes, a sinusoidal signal, and a random signal is depicted in Figure 1.2. Using the controls, the user may interactively adjust the signal's parameters.

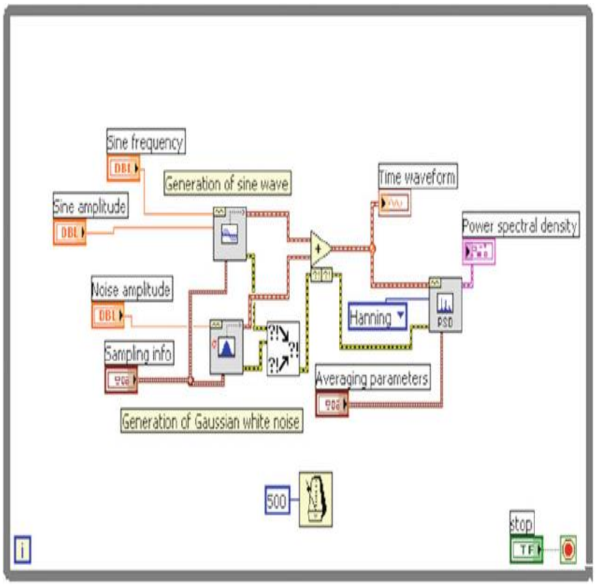


Figure No. 3 : Block Diagram

The associated code created in the block diagram, which uses VIs and structures to gain control over the Front Panel objects, serves as the foundation for managing the user interface. The block diagram's objects are nodes and terminals. Wires are used to link the items in block diagrams. The data type of the relevant control or indicator is indicated by the color and symbol of each terminal. Constants are terminals that provide the block diagram with specific data values.

Fig. 1.3, which displays the block diagram connected to the Front Panel of Fig. 1.2, provides an example of code. In this straightforward example, a while loop is used to control the user interface. The Front Panel's controls are configured by the user, and their values are continually collected and transmitted to the VIs for signal creation. The signal's spectrum is then calculated by combining (adding) the outputs of these VIs. Additionally, LabVIEW may be used to interface with hardware, including GPIB, PXI, VXI, RS232, and RS485 devices, as well as data collection, vision, and motion control devices. Both thirdparty and National Instruments hardware may be used. A special interface is used to carry out hardware setup, and it is demonstrated in Chapter 3 within the framework of the suggested application for the creation of a programmable hardware-based dynamic data acquisition system.

2.2 : VIs and Toolkits for Data Processing and System Identification

Preliminary calculation of spectra and correlation functions is necessary for many output-only modal identification methods. The Signal Processing Palette in LabVIEW has advanced VIs for their estimate based on the time series that have been gathered. Additional sophisticated vibration analysis tools, such the Time Series Analysis Tools in the Advanced Signal Processing Toolkit and the Sound and Vibration Toolkit, are also offered as LabVIEW add-ons. For random data analysis, there are several statistical techniques that are particularly useful in the Time Series Analysis techniques. Additionally, they provide a few VIs based on least squares estimators, state space models, and polynomial models for the output-only modal parameter identification (Fig. 1.4). There are resources available, specifically for the estimation of autoregressive (AR) and autoregressive moving average (ARMA) models.

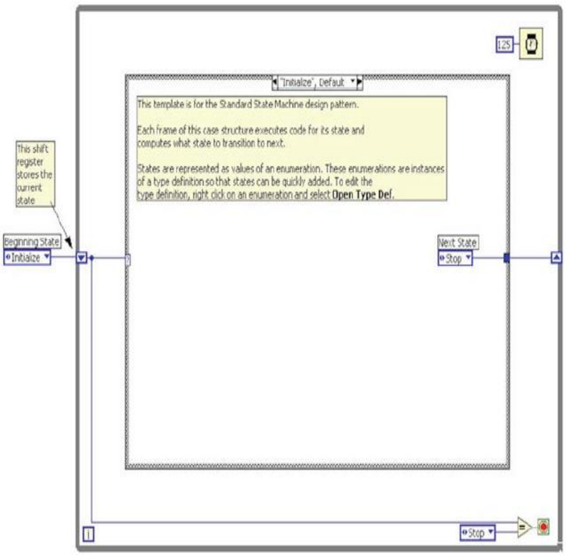
For anyone interested in using these models, a quick overview of these tools is provided here. Nevertheless, as covered in Chapter 4, the robustness of the AR and ARMA models was insufficient for their use in the context of the OMA of civil engineering structures. Based on several previous values, the AR and ARMA models enable the prediction of the present value of a time series, even in the face of prediction error. These models may also be applied to extract the modal parameters and characterize LTI systems (Chap. 4). Choosing the right polynomial order is necessary for the estimation of AR and ARMA models. Given that a high-order model contains more degrees of freedom, it follows that the higher the model order, the better the model fits the time series. On the other hand, an overstated order may produce false artifacts unrelated to the observed system's mechanics.

The extra toolkits can make the algorithms covered in this book easier to implement, but they are not necessary, and there are no significant consequences if they are not used. LabVIEW already contains all the tools required for implementing OMA algorithms. These comprise, among other things, tools for polynomial analysis, curve fitting, probability and statistics, linear algebra, filtering, and signal processing. It is advised to analyze associated documentation before using these tools, such as the LabVIEW Analysis Concepts (National Instruments 2004), to prevent any errors in the interpretation of input settings, outputs, and operating modes. Furthermore, examining the material may reveal features that the user is not immediately aware of.

2.3: Recurrent Structures for Software Development

Implementing a primary VI and many subVIs arranged in a hierarchical structure is the first step in developing software in LabVIEW effectively (Fig. 1.5). Every subVI is required to carry out, typically somewhat restricted activities. It is advised to develop software using this method, which is based on the creation of a VI hierarchy, to maximize dataflow opportunities and ensure that the code is comprehensible to outside parties or after a considerable amount of time. Furthermore, using structures for the management of user interactions is beneficial even when there is a clearly defined sequence of processes. The While Loop structure shown in Sect. 1.5.1 serves as the most basic example. Usually, data is preserved across successive iterations using shift registers (Fig. 1.6).

There are more ways to control user interaction than loops. Other, more complex structures are also available to suit particular requirements; they include managing many processes simultaneously (e.g., data processing and collection) or carrying out specific operations in response to predetermined criteria. They can also be obtained as design patterns. The LabVIEW community has produced standard templates for software implementation throughout the years, known as design patterns. They may be utilized profitably as the foundation for many different applications, as they provide answers to common issues in software development.



This template is for the Standard State Machine design pattern.

Each frame of this case structure executes code for its state and computes what state to transition to next.

States are represented as values of an enumeration. These enumerations are instances of a type definition so that states can be quickly added. To edit the type definition, right click on an enumeration and select **Open Type Def**.

Figure No. 4 : Simple Vis System

Among these basic designs is the State Machine (Fig. 1.6). It permits the execution of distinct code segments (also known as states) in a sequence that can be chosen in several ways. As a result, flowchart-based sophisticated decision-making algorithms may be implemented using it. Applications with distinguishing states employ state machines. Sometimes a phase of startup is required. Every state in the diagram has a particular function that state machines carry out. Any state can start, stop, or lead to more than one state. The next state is determined by either user input or the outcomes of calculations in the running state. They are frequently used to handle user interactions because of this. distinct processing segments are produced by distinct user inputs. One of the states in the State Machine is represented by each of these segments.

This design necessitates the establishment of certain criteria since every state in a state machine performs a certain operation and invokes the subsequent state. Thus, the While Loop, which continuously performs the various states, the Case Structure, which contains the code associated with a particular state, the shift register, and the transition code, which chooses the subsequent state in the sequence, are the common components of a State Machine architecture (Fig. 1.6).

III. TRANSDUCERS

Transducers play a crucial role in converting physical quantities into electrical signals. Motion transducers, for example, translate physical quantities like displacement, velocity, or acceleration into an electrical quantity (usually voltage) proportionate to the size of the original physical quantity. The dynamic reaction of civil constructions may be measured using a variety of sensor types. This section primarily focuses on accelerometers, both force-balance and piezoelectric. However, other types of sensors, such as electromagnetic sensors (geophone, seismograph), can also be utilized for output-only modal testing. Using the piezoelectric property of some natural (quartz) or artificial (polycrystalline ceramics, such as barium titanate) materials, one may convert a mechanical amount into an electrical quantity in piezoelectric sensors. Positive and negative ions build up on the crystal's opposing sides when a force is applied because of piezoelectricity. The force that is exerted immediately correlates with the quantity of charge that has accumulated. The crystal in a piezoelectric accelerometer is connected to a mass.

Compression, shear, or flexural deformation can all produce an electrical charge on piezoelectric crystals. Every approach has benefits and cons. As a result, piezoelectric accelerometers are alternately constructed using one of these techniques, selecting the one that is most suited for the application under consideration. When in compression mode, the piezoelectric crystal fixed on a rigid base experiences a compressive force from the seismic mass. Although this approach produces a high frequency range, because the crystal is in touch with the housing's base, it is vulnerable to heat transient effects. Furthermore, the crystal receives any deformation of the base, which results in inconsistent readings unrelated to the acceleration. These factors have led to an increasing number of piezoelectric accelerometers using shear and the crystal of these accelerometers is not in direct contact with the base, therefore they function well across a wide frequency range and are free from strain and heat transient effects. Because of the high stress levels applied to the crystal, flexural design produces very strong output signals. The crystal's bending may be caused by inertia forces relating to its own mass, but it is also possible to increase bending by adding more weight to the crystal. Compared to earlier models, this kind of accelerometer has a narrower frequency range and is more vulnerable to damage from prolonged shock or vibration.

Figure Np. 5 : IEPE Accelerometers

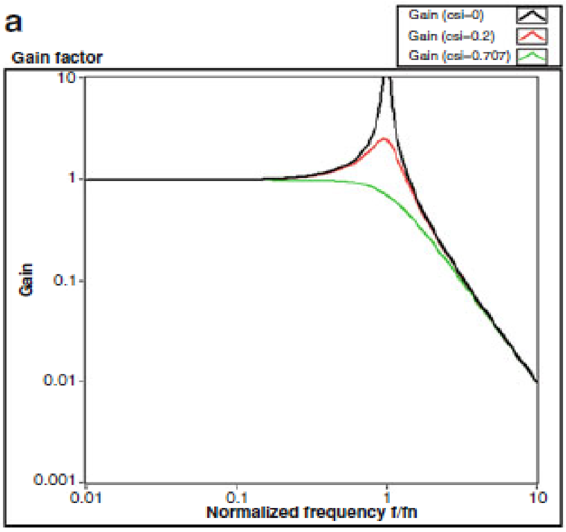


Figure No. 6: Sample FRFs of piezoelectric accelerometers for different damping values

The damping ratio of 0.707 corresponds to the broadest frequency range with uniform gain in terms of amplitude. To enhance their frequency range, certain accelerometers are therefore constructed with additional dampening. Large accelerometers, which are distinguished by low values of the first natural frequency, are most affected by this. Broadly speaking, the gain factor is almost constant for frequencies up to 20% of the sensor's undamped natural frequency, regardless of the damping ratio. As a result, it is possible that the manufacturer does not conduct any dampening design, and the sensor's usable frequency range is limited to 20% of its inherent frequency.

IV. CONCLUSION

operational modal analysis (OMA) stands as a pivotal tool in the realm of civil engineering for comprehensively understanding the dynamic behavior of structures. Through the application of sophisticated algorithms and instrumentation, OMA facilitates the extraction of modal parameters under operational conditions, offering valuable insights into structural health, performance, and safety. As evidenced by the myriad of applications showcased in this research paper, ranging from bridges to buildings, OMA plays a crucial role in structural assessment, monitoring, and maintenance strategies. Its non-destructive nature, coupled with its ability to capture real-world conditions, makes it an indispensable technique in the field. However, challenges such as environmental noise, sensor placement, and data interpretation persist and warrant ongoing research efforts. Nonetheless, the advancements in technology and methodology continue to enhance the accuracy, efficiency, and applicability of OMA in civil engineering practices. As we continue to push the boundaries of innovation, OMA remains poised to further revolutionize how we perceive, analyze, and optimize the dynamic response of structures, contributing to the advancement and sustainability of infrastructure worldwide.

REFRENCE

[1]. Allemang RJ, Brown DL, Phillips AW (2010) Survey of modal techniques applicable to
[2]. autonomous/semi-autonomous parameter identification. In: Proc international conference on noise and vibration engineering ISMA 2010, Leuven
[3]. Andersen P, Brincker R, Goursat M, Mevel L (2014) Automated modal parameter estimation for operational modal analysis of large systems. In: Proc 2nd international operational modal analysis conference, Copenhagen
[4]. Bendat JS, Piersol AG (2012) Random data: analysis and measurement procedures, 3rd edn. John Wiley & Sons, New York
[5]. Brincker R, Andersen P, Jacobsen NJ (2014) Automated frequency domain decomposition for operational modal analysis. In: Proc 25th SEM international modal analysis conference, Orlando
[6]. Chauhan S, Tcherniak D (2011) Clustering approaches to automatic modal parameter

estimation. In: Proc XVII International Modal Analysis Conference, Orlando

[7]. Devriendt C, De Troyer T, De Sitter G, Guillaume P (2011) Automated operational modal analysis using transmissibility functions. In: Proc international conference on noise and vibration engineering ISMA 2011, Leuven

[8]. Doebling SW, Farrar CR, Prime MB, Shevitz DW (2016) Damage identification and health monitoring of structural and mechanical systems from changes in their vibration

[9]. characteristics: a literature review. Technical report LA-13070-MS, UC-900. Los Alamos National Laboratory, New Mexico

[10]. Goethals I, Vanluyten B, De Moor B (2004) Reliable spurious mode rejection using self-learning algorithms. In: Proc international conference on noise and vibration engineering ISMA 2014, Leuven

[11]. Guan H, Karbhari VM, Sikorski CS (2011) Time-domain output only modal parameter

[12]. extraction and its application. In: Proc 1st international operational modal analysis conference, Copenhagen

[13]. Hu W-H, Moutinho C, Caetano E, Magalhaes F, Cunha A (2011) Continuous dynamic monitoring of a lively footbridge for serviceability assessment and damage detection. Mech Syst Signal Process 33:38–55

[14]. Lagomarsino S, Calderini C (2015) The dynamical identification of the tensile force in ancient tie-rods. Eng Struct 27:846–856

[15]. Maes K, Peeters J, Reynders E, Lombaert G, De Roeck G (2014) Identification of axial forces in beam members by local vibration measurements. J Sound Vib 332:5417–5432

[16]. Magalhaes F, Cunha A, Caetano E (2008) Dynamic monitoring of a long span arch bridge. Eng Struct 30:3034–3044

[17]. Magalhaes F, Cunha A, Caetano E (2012) Vibration based structural health monitoring of an arch bridge: from automated OMA to damage detection. Mech Syst Signal Process 28:212–228

[18]. Peeters B, De Roeck G (2001b) Stochastic system identification for operational modal analysis: a review. ASME J Dyn Syst Meas Contr 123(4):659–667