Experimental Modal Analysis of Civil Engineering Structures

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This article presents the evolution of experimental modal analysis in the civil engineering field, from input-output to output-only modal identification techniques. Many case histories are included from the experiences of the authors at the Laboratory of Vibrations and Monitoring at the University of Porto.

Decades ago, a major concern of structural engineers was the development and application of new and powerful numerical methods for the static and dynamic analysis of large civil engineering structures. The rapid development of finite-element techniques accompanied by tremendous technological progress in the field of personal computers allowed structural designers to use software packages for accurate simulation of structural behavior.

However, the design and construction of more and more complex and ambitious civil structures, like dams, large cable-stayed or suspension bridges, or other special structures have led structural engineers to develop new experimental tools to enable the accurate identification of the most relevant static and dynamic properties. These tools would provide reliable data to support calibrating, updating, and validating of structural analysis numerical models used at the design stage.

The continuous ageing and subsequent structural deterioration of a large number of existing structures have encouraged the development of efficient vibration-based damage detection techniques supported by structural health monitoring systems. The natural tendency of civil engineering researchers was to utilize well established input-output modal identification techniques to accurately identify the main dynamic properties of civil structures.

However, it is difficult to excite large civil structures in a controlled manner. Fortunately, remarkable technological progress in transducers and analog-to-digital converters has supported modal analysis of large structures exclusively based on measuring the structural response to ambient excitations and applying suitable stochastic modal identification methods.

The main purpose of this article is to briefly present our perspective concerning the evolution of experimental modal analysis in the civil engineering field, from input-output to output-only modal identification techniques. This discussion is strongly influenced by our experience as researchers.

Input-Output Modal Identification

Equipment and Test Procedures. Conventional modal testing is based on estimating a set of frequency response functions (FRFs) relating the applied force and corresponding response at several pairs of points along the structure with enough high spatial and frequency resolution. The construction of FRFs requires use of an instrumentation chain for structural excitation, data acquisition, and signal processing.

In small and medium-size structures, the excitation can be induced by an impulse hammer (Figure 1a) similar to those currently used in mechanical engineering. This device has the advantage of providing a wide-band input that is able to stimulate different modes of vibration. The main drawbacks are the relatively low frequency resolution of the spectral estimates (which can preclude the accurate estimation of modal damping factors) and the lack of energy to excite some relevant modes of vibration. Due to this problem, some laboratories have built special impulse devices specifically designed to excite bridges (Figure 1d). An alternative, also derived from mechanical engineering, is the use of large electrodynamic shakers (Figure 1c), which can apply a large variety of input signals (random, multi-sine, etc.) when duly controlled both in frequency and amplitude using a signal generator and a power amplifier. The shakers have the capacity to excite structures in a lower frequency range and higher frequency resolution. The possibility of applying sinusoidal forces allows for the excitation of the structure at resonance frequencies and, consequently, for a direct identification of mode shapes.

Figure 1. (a) Impulse hammer; (b) eccentric mass vibrator; (c) electrodynamic shaker over three load cells; d) impulse excitation device for bridges (K.U. Leuven).

The controlled excitation of large civil engineering structures requires the use of heavy excitation equipment. One option frequently used in the past in dynamic testing of dams was the eccentric mass vibrator (Figure 1b), which enables the application of sinusoidal forces with variable frequency and amplitude. The main drawbacks of this technique are low force amplitude induced at low frequencies, some difficulty in measuring the applied force, and restraining relative movement of the vibrator with regard to the structure. A better option, in terms of providing a wide-band excitation over the most interesting frequency range for large civil structures, is the use of servo-hydraulic shakers. For example, Figure 2 shows two shakers of this type built at EMPA to excite bridges or dams

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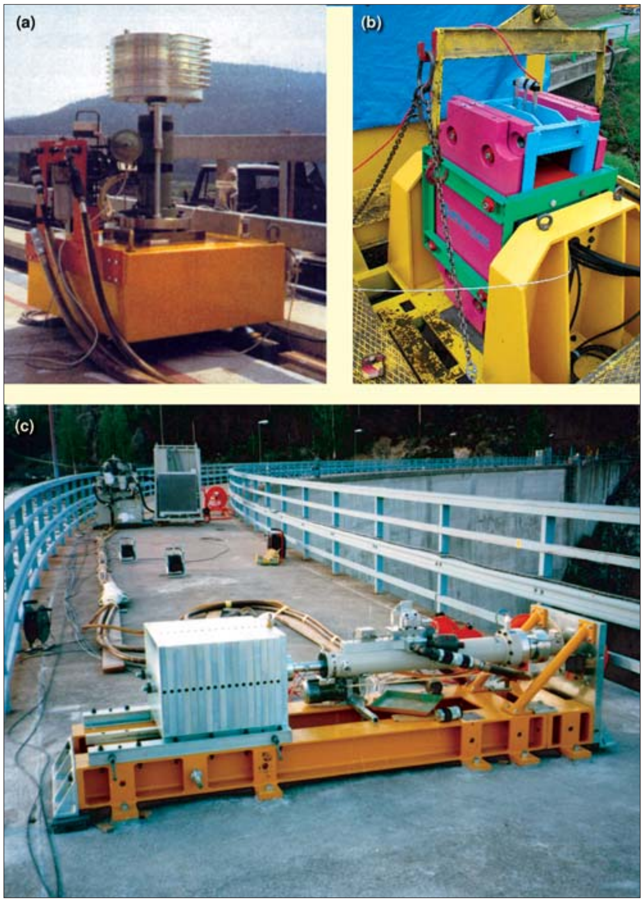


Figure 2. Servo-hydraulic shakers to excite: (a) bridges, vertically; (b) electro-hydraulic shaker from Arsenal Research; (c) dams, laterally (EMPA).

vertically and laterally, as well as an electro-hydraulic mass reaction shaker from Arsenal Research.

The dynamic response of a structure is usually measured with accelerometers – piezoelectric, piezoresistive, capacitive or force balance,[1] due to their relatively low cost and high sensitivity (see Figure 3). A particular characteristic of piezoelectric accelerometers is that they don't need a power supply and operate well over a wide frequency range. However, most are not suited to low-frequency applications. On the contrary, piezoresistive, capacitive, and force-balance accelerometers can provide DC or low-frequency response capability. The electrical signals generated by these transducers are usually rather low and must be amplified by conditioning units that may also provide anti-aliasing, low-pass filtering (allowing lower sampling rates), and analog integration to velocities or displacements.

The data acquisition and storage of dynamic data requires the use of an analog-to-digital (A/D) converter in the measurement chain. Raw data must be initially analyzed and processed; considering operations of scale conversion, trend removal, and decimation. Subsequently, the acceleration time history can be multiplied by appropriate time windows (Hanning, Cosine-Taper, etc.), to reduce leakage effects, and subdivided into different blocks for evaluation of average spectral, auto spectral, and cross spectral estimates using the FFT algorithm. Finally, FRFs (frequency response functions) can be obtained using estimators H_1 or H_2.[1] The automatic evaluation of FRFs requires appropriate software for analysis and signal processing, which is already available in commercial Fourier analyzers. These analyzers are sometimes implemented by a laptop PCMCIA card to allow either the acquisition of data through input channels or the control of a shaker through an output channel.

Input-Output Modal Identification Methods. There is a wide variety of input-output modal identification methods whose application relies either on estimates of a set of FRFs or on the corresponding impulse response functions (IRFs), which can be obtained through the inverse Fourier transform. These methods attempt to perform some fitting between measured and theoretical functions and employ different optimization procedures and different levels of simplification. Accordingly, they are usually classified according to the following criteria:

- Domain of application (time or frequency)
- Type of formulation (indirect or modal and direct)
- Number of modes analyzed (SDOF or MDOF – single degree of freedom or multi degree of freedom)
- Number of inputs and type of estimates (SISO, SIMO, MIMO, MISO – single input single output, single input multi output, multi input multi output, multi input single output).

Early methods of identification were developed for the frequency domain. For simple SDOF formulations (peak amplitude, curve-fit, inverse methods, for example), the fit between a measured and a theoretical FRF of a SDOF system in the vicinity of each resonant frequency is developed; neglecting the contribution of resonant modes. In more sophisticated MDOF methods – rational fraction polynomial (RFP), complex exponential frequency domain (CEFD), polyreference frequency domain (PRFD) – the fit between measured and theoretical FRFs is made globally for a wide range of frequencies.

Time-domain methods, which tend to provide the best results when a large frequency range or a large number of modes exist in the data, were developed because of limitations in the frequency resolution of spectral estimates and leakage errors in the estimates. The most widely known methods are either indirect – complex exponential (CE), least-squares complex exponential (LSCE), polyreference complex exponential (PRCE), Ibrahim time domain (ITD), eigen system realization algorithm (ERA), or direct autoregressive moving-average (ARMA).

The gradual development of all these methods, which are extensively described by Maia, *et al*,[1] tend to be completely automated systems of acquisition, analysis, processing, and identification, instead of interactive programs initially. Beyond that, the best-performing methods have been implemented in robust modal analysis software.[2] A special class of modal identification methods, called tuned-sinusoidal methods (e.g. Asher, Mau) corresponds to the particular type of tests that are based on the application of a sinusoidal excitation at each natural frequency, which can be implemented using eccentric mass vibrators.

Examples of Forced Vibration Tests. The performance of classical input-output modal identification tests in civil engineering structures can be of interest both for physical models and for prototypes. Figures 4 and 5 show a physical model of Jindo Bridge (South Korea), which was extensively tested to analyze the importance of dynamic cable-structure interactions in terms of seismic response analysis.[3] Several forced vibra-

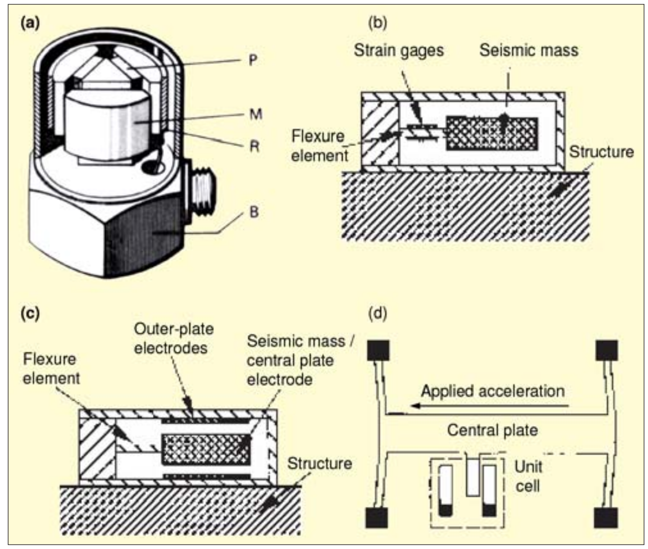


Figure 3. Schematic cross-section of accelerometers: (a) piezoelectric; (b) piezoresistive; (c) capacitive; (d) force balance.

Figure 4. (a) Jindo cable-stayed bridge; (b) physical model on shake table (EERC, Univ. Bristol); (c) physical model on shake table (ISMES).

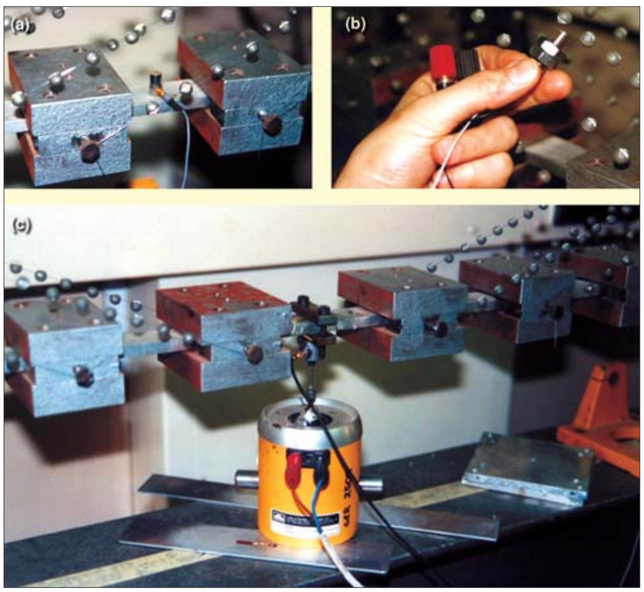
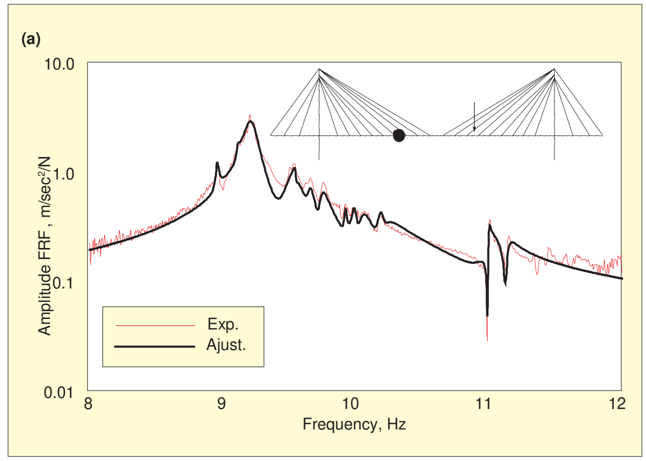


Figure 5. Application of electro-dynamic shaker: (a) response measurement with piezoelectric accelerometer; (b) measurement of cable tension; (c) whole unit.

tion tests were performed using electro-dynamic shakers (at the University of Bristol and ISMES) and considering two alternative configurations for the model. First, additional masses were distributed along the cables according to the similitude theory to idealize the cables' mass and consider lateral cable vibration. In a second phase, no distributed additional mass were introduced along the cables, but equivalent masses were concentrated at their extremities. This study identified the existence of different sets of multiple modes; some being pure cable modes and others coupled modes. Each of these sets presents a common shape for the deck and towers and different cable motions. The corresponding natural frequencies are very close, always in the vicinity of a global mode of the primary system (Figure 6).

Several large civil engineering structures, like buildings, bridges or dams, have also been subjected to forced vibration tests in the past using heavy excitation devices only available at well equipped laboratories. That was the case of EMPA, where Cantieni and other researchers have tested a significant number of bridges and dams.[4-6] Figures 7 through 9 show some examples of that remarkable activity, presenting in particular some of the modes of vibration accurately identified at the Swedish Norsjö dam.



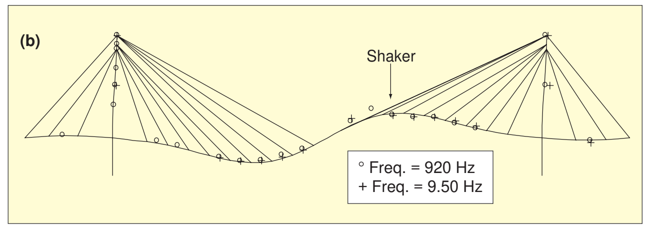


Figure 6. (a) amplitude of FRF relating vertical acceleration at 1/3 span with the vertical force applied at the opposite 1/3 span; (b) identified pattern of a set of multiple modes.

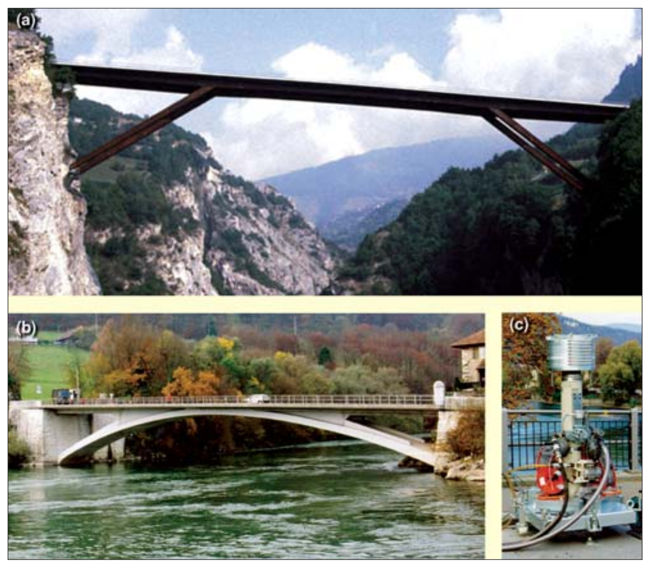


Figure 7. (a) Dala bridge; (b) Aarburg bridge; (c) electro-hydraulic vibrator used at Aarburg bridge.

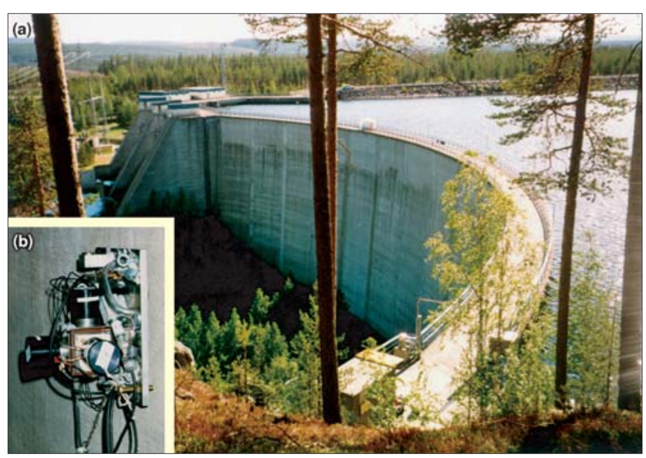


Figure 8. (a) Norsjö dam; (b) view of instrumented point at downstream side of reinforced concrete wall.

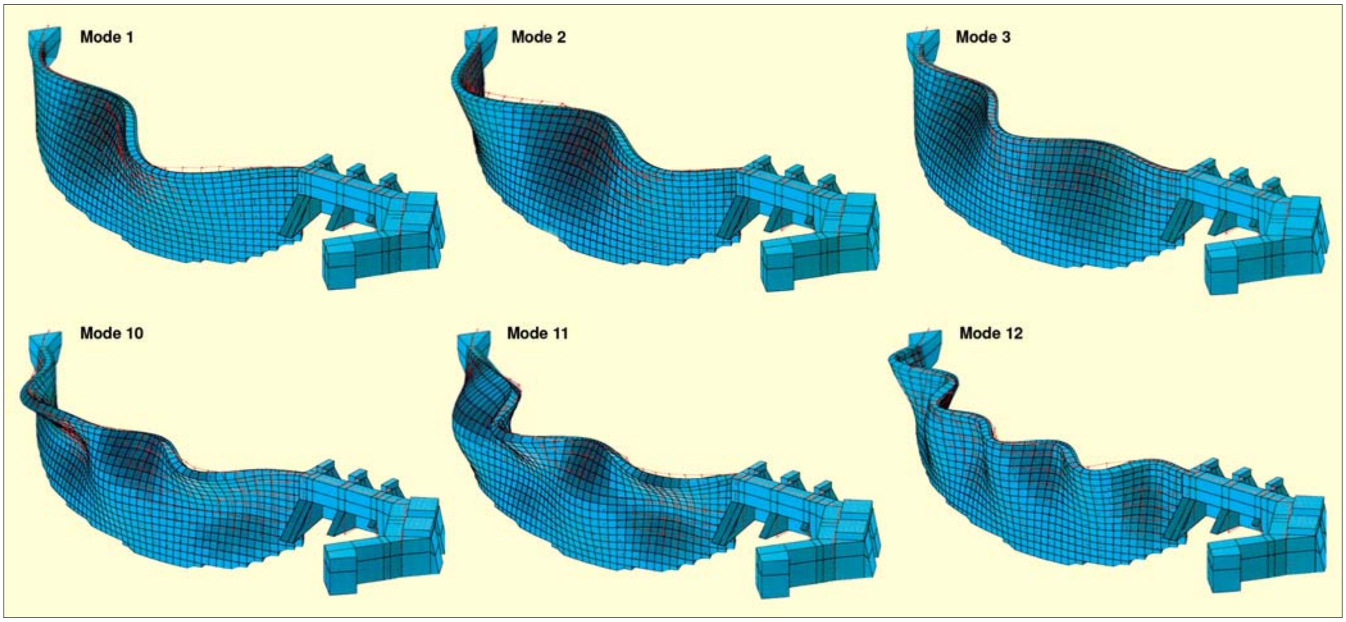


Figure 9. Some identified modes of vibration at Norsjö dam (modes 1, 2, 3, 10, 11, 12).

Output-Only Modal Identification

The main problem associated with forced vibration tests on bridges, buildings, or dams stems from the difficulty in exciting the most significant modes of vibration in a low range of frequencies with sufficient energy and in a controlled manner. In very large, flexible structures like cable-stayed or suspension bridges, the forced excitation requires extremely heavy and expensive equipment usually not available in most dynamic labs. Figure 10 shows the impressive shakers used to excite the Tatara and Yeongjong bridges.

Fortunately, recent technological developments in transducers and A/D converters have made it possible to accurately measure the very low levels of dynamic response induced by ambient excitations like wind or traffic. This has stimulated the development of output-only modal identification methods.

Therefore, the performance of output-only modal identification tests became an alternative of great importance in the field of civil engineering. This allows accurate identification of modal properties of large structures at the commissioning stage or during their lifetime without interruption of normal traffic.

Equipment and Test Procedures. Modern force-balance accelerometers (Figure 11a) are well suited for measurements in the range of 0-50 Hz and are virtually insensitive to high-frequency vibrations. They have contributed significantly to the success of ambient vibration tests. In such tests, the structural ambient response is captured by one or more reference sensors at fixed positions and with a set of roving sensors at different measurement points along the structure and in different setups. The number of points used is conditioned by the spatial resolution needed to characterize appropriately the shape of the most relevant modes of vibration (according to preliminary-finite element modeling), while the reference points must be far enough from the corresponding nodal points.

Force-balance accelerometers require an appropriate power supply, and their analog signals are usually transmitted to a data acquisition system with an A/D conversion card of at least 16 bits through relatively long electrical cables. This system can be implemented on a normal PC. Some data acquisition and processing systems, specifically designed for ambient vibration tests, are already available (Figure 11b). They are similar to the Fourier analyzers used for classical experimental modal analysis.

Most output-only modal identification tests in large civil structures have been based worldwide on the use of long electrical cables. Implementation of this solution is cumbersome and time consuming. Wireless systems are being developed to avoid this problem or at least drastically reduce cable length

Figure 10. Forced vibration tests: (a) Tatara cable-stayed bridge; (b) Yeongjong suspension bridge; (c) high force shaker.

through local digitization and single-cable signal transmission. A very efficient alternative has been intensively used at FEUP[7] and LNEC[8] based on triaxial seismic recorders synchronized through GPS sensors.

Output-Only Modal Identification Methods. Ambient excitation usually provides multiple inputs and a wide-band frequency content thus stimulating a significant number of vibration modes. For simplicity, output-only modal identification methods assume that the excitation input is a zero-mean Gaussian white noise This means that real excitation can be expressed as the output of a suitable filter excited with white noise input. Some additional computational poles without physical meaning appear as a result of the white noise assumption.

There are two main groups of output-only modal identification methods – nonparametric methods essentially developed in the frequency domain and parametric methods in the time domain. The basic frequency domain method (peak-picking), though already applied some decades ago to the modal identification of buildings[9,10] and bridges[11,12], was only conveniently implemented by Felber[13] about 12 years ago. This approach, which leads to estimates of operational mode shapes, is based on the construction of average normalized power spectral den-

Figure 11. (a) Force balance accelerometers; (b) multichannel data acquisition and processing system for ambient vibration tests; (c) strong motion triaxial seismograph

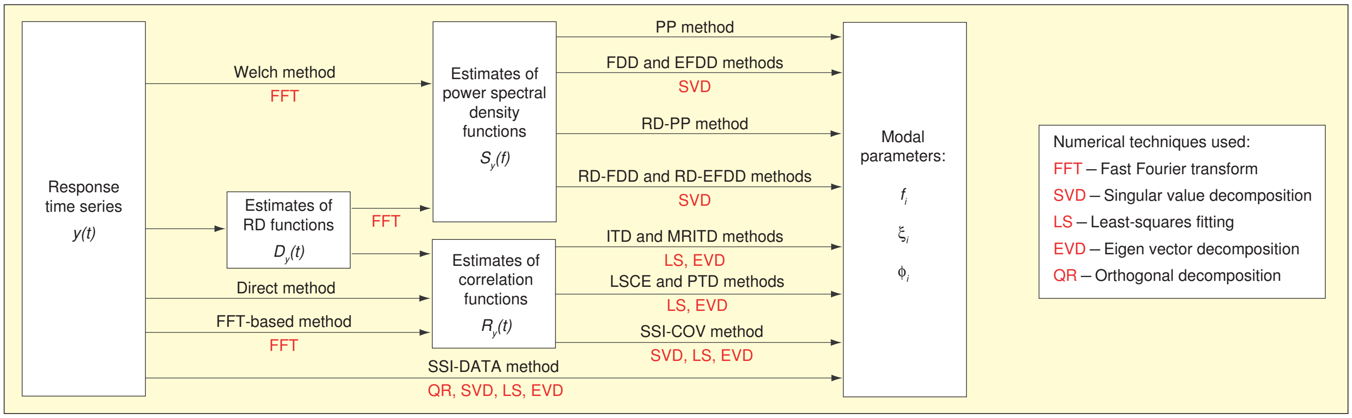


Figure 12. Schematic representation of output-only modal identification methods.

sities (ANPSDs) and ambient response transfer functions involving all the measurement points. This allowed the development of software for modal identification and visualization used at UBC and EMPA.[13] The frequency domain approach was subsequently improved[14,15] by performing a single-value decomposition of the matrix of response spectra to obtain power spectral densities of a set of SDOF systems. This method, frequency domain decomposition (FDD), was implemented by Brincker, *et al.*,[16] and subsequently enhanced[17] to extract modal damping factor estimates. In this last approach (EFDD), these estimates are obtained through inspection of the decay of auto-correlation functions evaluated by performing the inverse Fourier transform of the SDOF systems' power spectral densities.

The time-domain parametric methods involve the choice of an appropriate mathematical model to idealize the dynamic structural behavior (usually time-discrete, state-space stochastic models, ARMAV or ARV) and the identification of the values of the modal parameters so the model fits the experimental data as well as possible following some appropriate criterion. These methods can be directly applied to discrete response time series or, alternatively, to response correlation functions. The evaluation of these functions can be made based on their definition using the FFT algorithm[18] or applying the random decrement method (RD).[19] A peculiar aspect of output-only modal identification based on the fitting of response correlation functions is the possibility to use methods that stem from classical input-output identification methods based on impulse response functions. Some of these methods are the Ibrahim time domain (ITD)[20], the multiple reference Ibrahim time domain (MRITD)[21], the least-squares complex exponential (LSCE) [22], the polyreference complex exponential (PRCE),[23] or the covariance-driven stochastic subspace identification (SSI-COV).[24]

An alternative method that allows direct application to the response time series is the data-driven stochastic subspace identification (SSI-DATA).[25] Note that the random decrement technique usually associated with the application of time-domain methods like Ibrahim's can also be the base for the application of frequency domain methods (like PP, FDD or EFDD).This leads to free vibration responses from which power spectral densities can be evaluated using the FFT algorithm,[26] thus reducing noise effects (methods RD-PP, RD-FDD and RD-EFDD). These methods, schematically represented in Figure 12, have been recently implemented, applied, and compared by Rodrigues.[8] Figure 12 also indicates the five different types of numerical techniques employed in their development (FFT, SVD, LS, EVD and QR).

A new operational polymax parameter estimation method was recently introduced by LMS.[27] It operates on spectra or half spectra (i.e. the Fourier transforms of the positive time lags of the correlation functions), and its main advantage consists in yielding extremely clear stabilization diagrams, making an automation of the parameter identification process rather straightforward and possibly enabling continuous monitoring of structural dynamic properties.

Examples of Ambient Vibration Tests. Ambient vibration tests have been performed with great success in large buildings, bridges, and other structures. High-quality experimental databases have been used to compare the performance of different output-only modal identification methods. A benchmark test concerning the modal identification of the Heritage Court Tower (Vancouver, Canada) was organized at IMAC-XVIII by Ventura.[28] This example considered a combination of measured signals (half-sum and half-difference signals along two orthogonal directions at two different points at each floor). This emphasized contributions from bending or torsion, as well as high-frequency resolution to separate contributions from close modes when using the classical PP method.[29] Applying FDD and SSI methods permitted a more automatic identification procedure for distinguishing close modes and extracting modal damping estimates (see Figure 13).

In the case of bridges, complete ambient vibration tests were developed along about 5 km of the Vasco da Gama Bridge by FEUP. Regarding the main cable-stayed bridge (Figure 14), the ambient structural response was measured during periods of 16 minutes at 58 points along the deck and towers (upstream and downstream) using a wireless system based on six triaxial, 16-bit seismographs synchronized by a laptop computer. The identification of a significant number of lateral, vertical, and

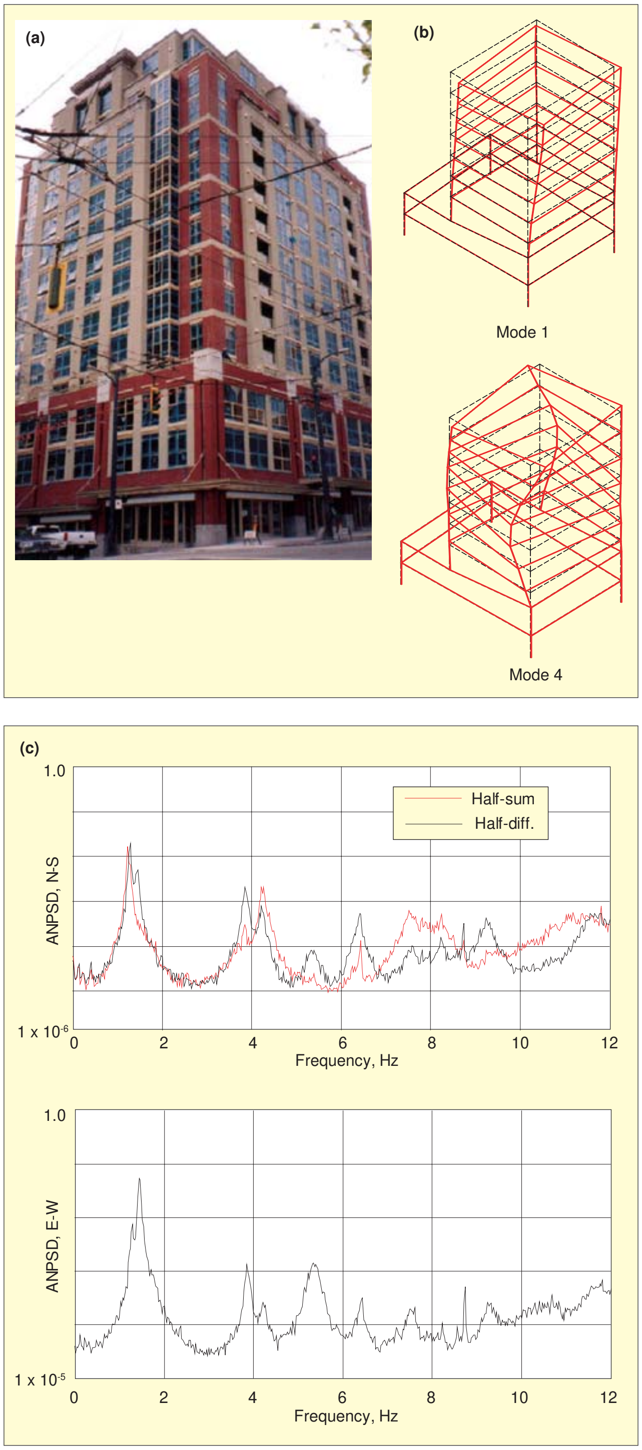


Figure 13. (a) Heritage Court Tower; (b) two identified mode shapes; (c) ANPSD spectra.

Figure 14. View of Vasco da Gama Bridge.

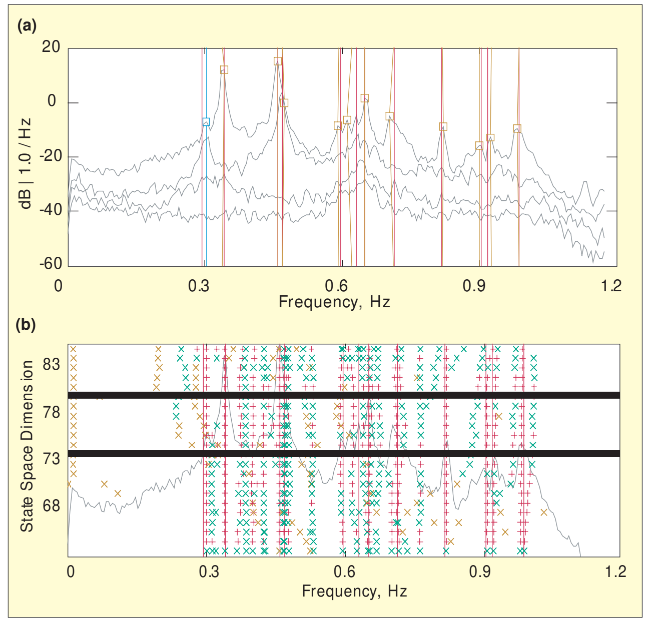


Figure 15. (a) Singular-value spectra; (b) stabilization diagram.

torsion modes in the relevant frequency range of 0-1 Hz was performed at first[7] using the PP method. Subsequently, SSI and FDD methods were applied[30,31] and compared using the software MACEC[24] and ARTeMIS[32]. This lead to estimates of modal damping factors, although very accurate damping estimates require longer measurement periods. Figure 15 shows the singular value spectra and a stabilization diagram generated by these two methods, while Figure 16 presents plots of some fundamental modes.

Note that the existence of cable components in the analysis frequency range can make identification of global natural frequencies difficult. Figures 17c and 17d show PSD (power spectral density) functions concerning the ambient response of the international Guadiana cable stayed-bridge (Figure 17a – linking Portugal to Spain in Algarve), evaluated with three different levels of average wind speed. This shows the appearance of spectral contributions from the fundamental modes of stay cables (in the range 0.6-0.9 Hz) or second harmonics leading to spectral peaks that cannot be interpreted as global natural frequencies of the bridge. Inspection of the spectral peaks (Figure 17b) shows the increase of modal damping with wind speed, which can be evaluated through ambient vibration tests using sufficiently long measurement periods.[33]

Note that the output-only modal identification technique used in Vasco da Gama and Guadiana bridges by FEUP has been recently applied with great success to the dynamic tests at the commissioning stage of the outstanding Millau viaduct, coordinated by Grillaud and Flamand (CSTB, France).[34]

Examples of Free Vibration Tests – Damping Estimation. The accurate identification of modal damping factors is a major problem in the identification process due to the considerably larger scatter associated with various natural frequency and mode shape estimates. This is also true because the viscous damping assumption does not correspond exactly to real damping characteristics. The modal damping ratios increase gradually with levels of oscillation.

In several circumstances, the accurate identification of modal damping factors is required, which is frequently achieved by performing a free vibration test. This situation is unique to large and slender cable-stayed or suspension bridges where knowledge of certain damping factors is crucial for assessing aeroelastic instability problems. Such tests have been performed at Normandy, Vasco da Gama, or Millau bridges. At Vasco da Gama Bridge, the test was made by suspending a barge on a cable with a mass of 60 tons from an eccentric point at the deck (Figure 18a)[7] at one-third span upstream. The cable was cut when the tide became low and the wind speed of less than 3 m/s to avoid the influence of aerodynamic damping. The sudden release of the mass caused a free vibration response, which was measured over 16 minutes by six triaxial seismographs at one-half and one-third span cross-sections. Similar techniques can be used on other structures, as is the case for

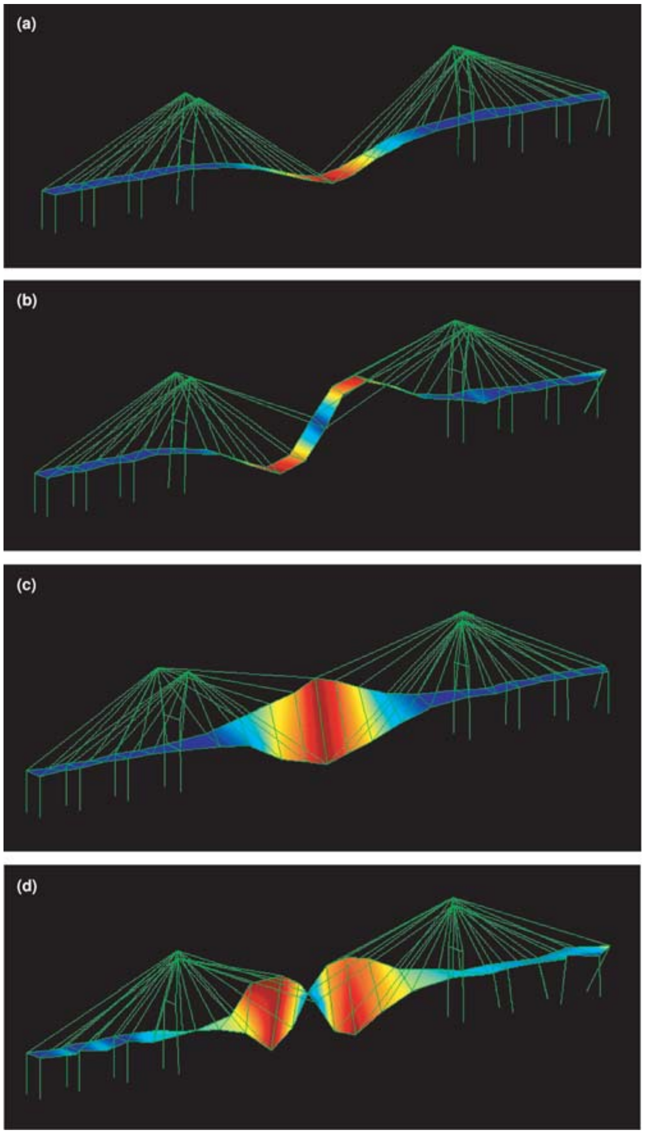


Figure 16. Identified modes: (a) first bending; (b) second bending; (c) first torsional; (d) second torsional.

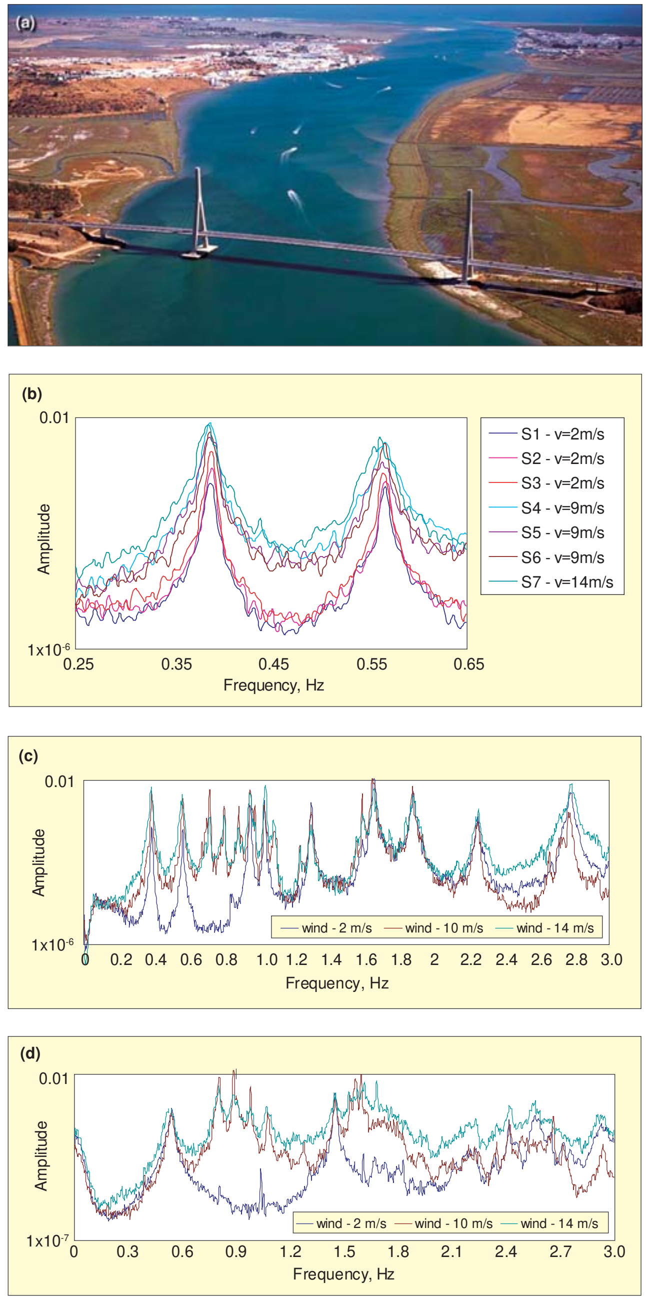


Figure 17. (a) Guadiana cable-stayed bridge; (b, c) PSD functions of half-sum vertical; lateral (d) acceleration at reference section as function of mean wind speed.

the Madeira airport extension[35] where a mass of 60.8 tons (Figure18b and 18c) was suspended from the deck. The sudden release of the mass was achieved via detonation of a fusible element incorporated in the suspension device.

The aeroeleastic stability of the cable roof of the new Braga Stadium (EURO'2004, Figure 19) was proven by different experimental tests on physical models. The modal damping identification was essentially required to study possible resonance effects that could affect long-term structural integrity and durability. Sinusoidal excitations were applied at different points by a mechanical vibrator connected to the cable roof. By stopping the vibrator suddenly, it was possible to measure modal-free vibration responses as plotted in Figure 19. The exponential fitting of the free vibration envelopes led to very accurate estimates of modal damping factors for different levels of oscillation.[36]

Finite-Element Correlation and Updating

Finite-Element Correlation. The modal identification of bridges and other civil structures is required for validation of finite-element models used to predict static and dynamic structural behavior either at the design stage or at rehabilitation. After appropriate experimental validation, finite-element models can provide essential baseline information that can subsequently be compared with information captured by long-term monitoring systems to detect structural damage.

The correlation of modal parameters can be analyzed both in terms of identified and calculated natural frequencies and by corresponding mode shapes using correlation coefficients or MAC (modal analysis criteria) values. Beyond that, modal damping estimates can be also compared with the values assumed for numerical modelling. This type of analysis has already been developed for the Vasco da Gama and Luiz I bridges with excellent results[7,37] and has recently been applied at two Portuguese bridges over Douro River (Figure 20). The New Hintze Ribeiro Bridge is a six span composite bridge that replaced the centenary bridge that collapsed in 2001 and the Pinhão Bridge (a three-span simply-supported metallic bridge with a concrete slab at the deck) is presently under rehabilitation.

In the first case (Figure 20a), good correlation between identified and calculated modal parameters was achieved for the vertical bending modes. Regarding the lateral response of the bridge, identified frequencies were higher than calculated values even though good correlation of modal shapes had been obtained.[38] Such a discrepancy stems from the difficulty in numerically simulating the real characteristics of soil-structure

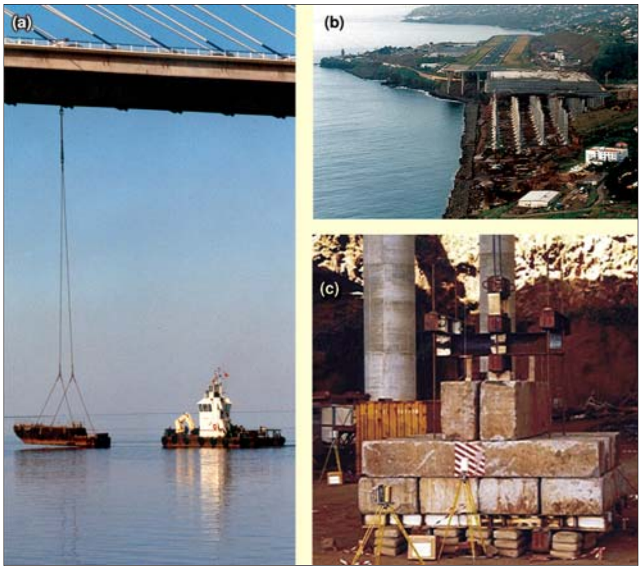


Figure 18. (a) Free vibration test of Vasco da Gama cable-stayed bridge; (b) aerial view of Madeira airport extension; (c) mass of 60.8 tons used in the free vibration test of Madeira airport extension.

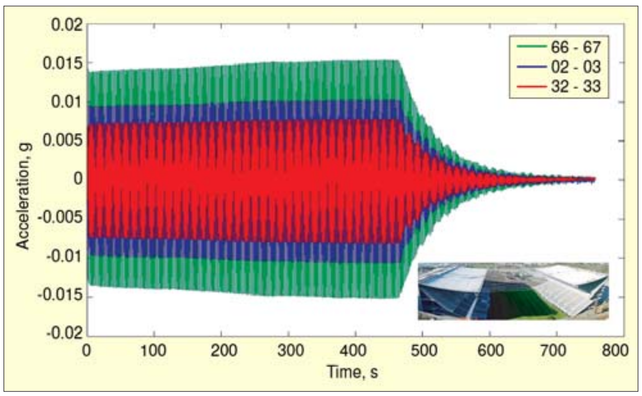


Figure 19. Measurement of free vibration response at three different points of Braga stadium cable-roof after inducing resonance.

interactions at the foundation of several piers and it shows the large influence that variations in boundary conditions can have on the global dynamic bridge properties.

In the case of the Pinhão Bridge (Figure 20b), very similar modal estimates were obtained in the three similar spans, and good correlation was achieved between significant identified and calculated modal parameters considering either the vertical or lateral behavior of the bridge. It was clear[39] that initial numerical modeling developed by the designer should be improved to correctly simulate the lateral dynamic response by including the stiffness associated with the concrete slab of the deck which was made through a discretization of shell elements.

Finite-Element Updating. The accurate identification of the most significant modal parameters based on output-only tests can support the updating of finite-element models, which may overcome several uncertainties associated with numerical modeling. Such updating can be developed on the basis of a sensitivity analysis using several types of models and changing the values of some structural properties to achieve a good match between identified and calculated modal parameters. This procedure has been followed recently to study the dynamic behavior of a stress-ribbon footbridge at the FEUP Campus (Figure 21). For that purpose, initial finite-element models were developed for the bridge deck as a set of beam elements with the geometry considered at the design stage or measured through a topographic survey (Models 1 and 2). Afterward, due to the clear nonlinear geometrical behavior of the bridge, a third model (Model 3) was developed. The deck was modeled in truss finite elements with the cable axial stiffness (neglecting

Figure 20. (a) New Hintze Ribeiro and (b) Pinhão bridges, over Douro River.

Figure 21. Stress-ribbon footbridge at FEUP Campus.

bending stiffness) and adjusting the initial cable tension to obtain the measured longitudinal profile after progressive application of the loads. To also take into account the bending stiffness of the concrete slab, this model was subsequently adapted (Model 4) by discretizing the deck in truss finite elements with progressive loading and activation of beam elements connecting the nodes of the truss elements. Finally, this model was slightly modified to consider partial rotations between beam elements and to simulate the lack of sealing of the joints. The area and inertia of the beam elements was also reduced to simulate the effects of cracking and lack of adherence between precast and *in situ* concrete. After all these iterations, very good correlation between identified and calculated natural frequencies and mode shapes was achieved.[40]

Beyond this type of sensitivity analysis, more automatic finite-element updating techniques can also be used.[41] The drawback of output-only modal identification is that it seems to be impossible to obtain mass normalized mode shapes. However, this inconvenience can be overcome[42] by introducing appropriate mass changes.

Conclusions

Civil engineering structures have peculiar characteristics (large size and relatively low natural frequencies) that make the current application of classical input-output modal identification techniques difficult. Therefore, there is presently a clear tendency worldwide to explore and improve the potential of output-only modal identification techniques, whose efficiency and accuracy were clearly illustrated with the applications shown. The techniques that may be used under normal operation conditions can provide a solid basis for:

- Developing finite-element correlation analyses.
- Finite-element updating and validation.
- Defining a baseline set of dynamic properties of the initially undamaged structure that can subsequently be used for the application of vibration-based damage detection techniques.
- Integrating output-only modal identification techniques in health monitoring systems.
- Implementing vibration-control devices.

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