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REVIEW

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# An Overview: The Application of Vibration-Based Techniques in Bridge Structural Health Monitoring

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**Abstract**

Structural health monitoring (SHM) systems have been developed to evaluate structural responses to extreme events such as natural and man-made hazards. Additionally, the increasing volume of users and vehicle sizes can lead to the sudden damage and collapse of bridge structures. Hence, structural monitoring and dynamic characteristic analyses of bridge structures are critical and fundamental requirements for bridge safety. SHM can overcome the weaknesses of visual inspection practices, such as lack of resolution. However, because of computational limitations and the lack of data analysis methods, substantial quantities of SHM data have been poorly interpreted. In this paper, the SHM of bridges based on dynamic characteristics is used to assess the "health state" of bridge structures. A comprehensive SHM system using vibration-based techniques and modal identification for bridge structures are well defined. Some advanced concepts and applications regarding bridge safety evaluation methods, including damage detection and load-carrying capacity, are reviewed. For the first time, the pros and cons of each vibration technique are comprehensively evaluated, providing an advantage to the authority or structural owner when developing a bridge management database. This information can then be used for continuous structural monitoring to access and predict the bridge structure condition.

**Keywords:** Structural health monitoring, Forced vibration test, Ambient vibration test, Modal identification, Experimental modal analysis

## 1 Introduction

In recent years, with the rapid development of sensor technology, numerical simulation methods, and damage diagnosis technology, structural health monitoring (SHM) has become widely used in bridge infrastructures (Xu et al., 2014). SHM technology can continuously provide reliable state of bridge structure and response information, identify deterioration and damage during design and construction, assess the effect of this damage on the bearing capacity and reliability of the bridge structure, and provide overload and damage warning information for bridge structure operations and maintenance decisions. As a result, SHM technology has increasingly become an efficient way of evaluating the health of a bridge structure. Increased awareness and familiarity with vibration-based SHM systems for highway bridges have emerged over the past few decades due to advancements in sensor and electrical infrastructure. Fig. 1 illustrates the application of vibration-based SHM in a variety of fields, with civil engineering being the most common application.

Vibrations on bridge structures can be caused by dynamic loads from human and traffic activities, wind

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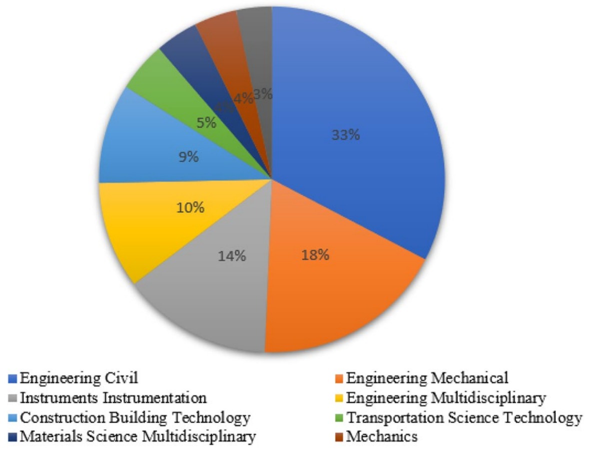


**Fig. 1** Application fields of vibration-based structural health monitoring (years 2000–2021)

power, and so on; hence, vibration analysis of a bridge's structure is a critical component of bridge structure analysis. Efficiently assessing the state of a bridge is crucial for ensuring its continued reliability, durability, and operational utility. This requires precise evaluation of the bridge's performance using cutting-edge diagnostic tools. These techniques applications are able in identifying the presence of the damage, address its location, and quantify the damage levels which are summarised as the damage detection and characterisation for maintenance activities (Mousavi et al., 2021).

A significant problem in designing an SHM approach for civil infrastructure is the lack of a baseline generated from type testing or the costly qualification procedures applicable to bridge constructions. The technique and devices used must be practical, not labour intensive, cost-effective, and easy to use in real applications. As a result, a unique feature of SHM for civil infrastructure is that a significant portion of the system must be focused on a long-term evaluation of what is 'normal' structural performance or the 'health state condition' (Aktan et al., 2001). Magalhães et al. constructed an SHM method for the Infante D. Henrique Bridge in Portugal, a 280-m concrete arch bridge, to evaluate the efficacy of modal parameter tracking for bridge SHM (Magalhães et al., 2012a). The Lupu Bridge is the world's second-longest arch bridge and features an SHM system. It is made of steel and features a half-trough tied-arch design. The system used measurements of strain, wind pressure, temperature, and acceleration to determine the bridge's status (Sun et al., 2009).

It is necessary to select the critical factors that are to be analysed, and these parameters must be properly measured to produce the desired results. Using data generated from an SHM system, Ding et al. examined the dynamic features of a high-speed railway arch bridge in China called the Dashengguan Yangtse bridge (Sun et al., 2009). Failures are avoidable if the dynamic characteristics of the bridge structure are known. The dynamic characteristics of a structure can be classified by three parameters, namely, natural frequencies, damping ratios, and mode shapes. These modal characteristics must be identified to properly identify the structure's dynamic behaviour.

However, there is limited literature on the implementation of an efficient SHM approach on a large scale. Alamdari et al. proposed a major SHM deployment for the 503-m-long Sydney Harbour Bridge (Alamdari et al., 2016). A sample of 800 jack arches located beneath traffic lane 7 was assessed for performance and structural deterioration using information gathered from the SHM system. SHM system implementations have been designed in Japan, Hong Kong, and later in North America for big bridge constructions throughout the past decade. This is due to the benefit that SHM systems offer a great deal of potential in terms of gaining insight into the condition of bridge structures (Wong, 2004).

In this paper, recent research trends are reviewed for the SHM of civil infrastructures. The periodic assessment and findings acquired by previous researchers highlight the advantages and limits of the methods. As a result, awareness of the techniques can be improved. To increase knowledge of this issue, this paper was written to provide a reasonably wide literature and background review of bridge dynamic characteristics in vibration-based SHM. This contribution will offer a useful opportunity for both beginners and experienced professionals to evaluate bridges dynamically. This paper focuses on the following: (1) determination of dynamic characteristics using dynamic testing methods, which include forced and ambient vibration tests; (2) existing modal identification (MI) algorithms for identifying the dynamic properties of a structure based on measured data; and (3) vibration-based SHM for detecting damage and structural capacity.

## 2 Dynamic Testing

Full-scale dynamic testing of structures can provide significant information on structure service behaviour and performance. With increased interest in the structural health of highway bridges, dynamic testing may be utilised to determine the bridge service state. Various testing methods and algorithms have been adopted from mechanical engineering, where dynamic phenomena and experimental modal analysis have been previously studied. Modal parameters (natural frequencies, mode shapes) can be obtained from the observed dynamic response caused by ambient, forced, or free excitation (Fig. 2). Analysis of available techniques should be carried

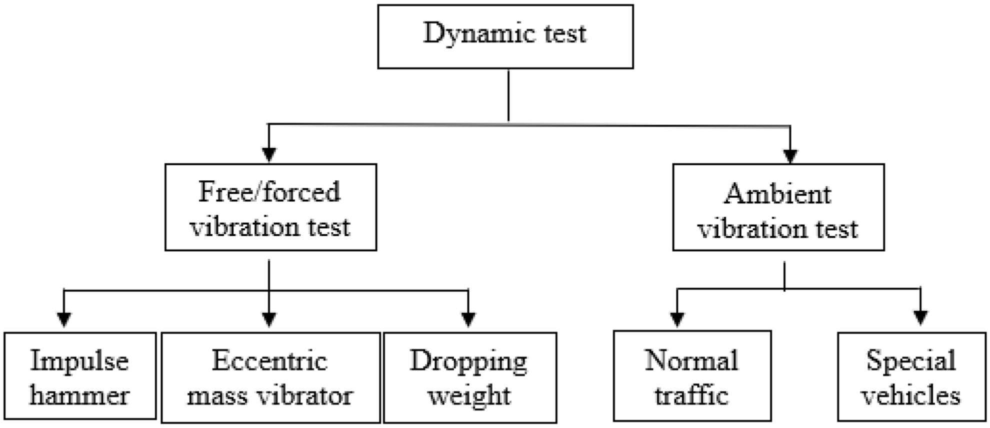


**Fig. 2** Illustration of the excitation instrument based on the characterisation of the dynamic test

out before selecting an appropriate testing method in terms of its applicability to a bridge monitoring system.

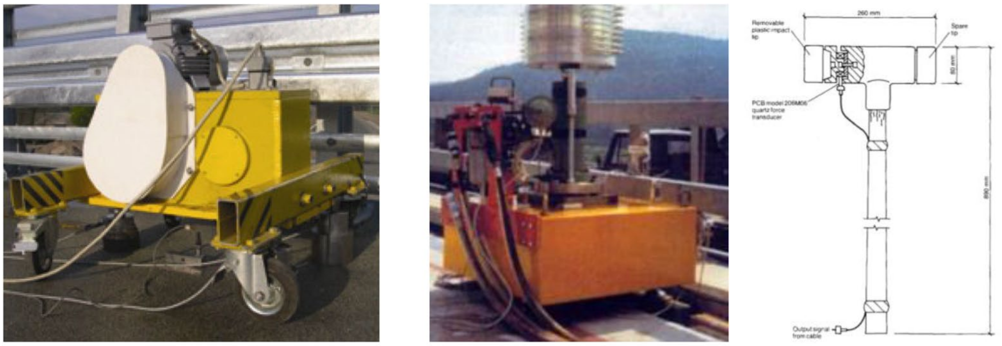
The main criterion of this systematic dynamic test of bridge monitoring is the method of structure excitation. The degree of control over the input excitation is the basis for the type of categorisation. The dynamic testing method in which the excitation is artificially induced is categorised under forced vibration testing (FVT). The forced vibration test is also known as a test with controlled input but is not measured. Methods, where the input excitation is not controlled, are classified as ambient vibration tests. The type of excitation devices and instrumentation used depends on the size of the structures to be tested. The advantages and disadvantages of the chosen testing techniques (Table 1), as well as the range of their application in bridge monitoring in terms of testing equipment, data processing, and analysing dynamic parameters, are explained in this section and demonstrated by instances of practical application.

### 2.1 Forced Vibration Test

Several studies have investigated the use of FVT and experimental modal analysis to identify damage to existing civil structures. This technique uses input excitation with known force levels at defined frequencies. Thus, the experimentalist has control over the input. Forced vibration tests offer the benefit of reducing extraneous noise effects in the observed structural response. The input loading can be changed to meet the test requirements. The bridge's vibrations can be excited by an impulse hammer (Fig. 3a), eccentric rotating mass vibrators (Fig. 3b), or an impulsive shaker (Fig. 3c). The excitation technique

**Table 1** Summarisation of the advantages and limitations of the force vibration test

| **Forced vibration testing (FVT)** | | |
|---|---|---|
| **Excitation instrument** | **Advantages** | **Limitations** |
| Impact hammer | A straightforward approach to excite the structure<br>Fast in their application and tests can be quickly repeated a large number of times<br>Giving a wide-band input that may trigger many vibration patterns | Susceptible to input noise<br>Higher impact hammer masses can cause the risks of local damage<br>Bridges must be closed to traffic during testing |
| Eccentric rotating mass vibrators | Precise results for medium to short span structures with medium-to-high damping<br>The input loading can be changed to meet the requirements of the test<br>Can be operated at various frequencies<br>Generating forces in more than one direction | The exciter needs laboratory testing to determine its parameters before its practical application<br>Bridges must be closed to traffic during testing |
| Servo-hydraulic shakers | Generate wide-band stimulation throughout the highest frequency range of interest | The size of the structure may be limited to the use of single input servo-hydraulic-based burst random noise excitation<br>Bridges must be closed to traffic during testing |



(a) Eccentric mass vibrator (b) A servo-hydraulic shaker (c) Impact hammer tools

**Fig. 3** Forced vibration test excitation technique (Zwolski & Bień, 2011)

is heavily influenced by the bridge's strength and the desired intensity of excitation.

An impulse hammer similar to those now used in mechanical engineering can be used to produce excitations in small- and medium-sized structures. This technique has the benefit of giving a wide-band input that may trigger many vibration patterns and is the most straightforward approach to excite the structure. In Maguire and Severn (1987), a 5.4-kg instrumented sledge hammer was introduced to test four 40-tonne bridge beams. The hammer's maximal impact force was estimated to be 22 kN. In this study, hammer testing is said to be a rapid and accurate way of determining the as-built structural dynamic characteristics. The mass of the impact hammer must increase as the bridge size increases. However, with higher impact masses, the impact hammer probably risks local damage at the site of structural contact when high force levels are applied. In a study by Bayraktar, a steel footbridge was subjected to FVT using an impact hammer to excite the bridge with low-amplitude wide-band excitations (Bayraktar & Şahin, 2014). This study indicates that the use of an impact hammer as excitation for FVT generated the best results for short bridges with spans < 30 m.

Instead of using an impact hammer for excitation, an eccentric mass vibrator is one of the earliest contacting vibrators for FVT and has been used for several years (Jeary & Sparks, 1977). The input loading, such as loading from an eccentric mass vibrator, can be changed to meet the requirements of the test. Vibrator machines may be a suitable solution for small- to medium-sized structures such as slabs or footbridges. These machines create vibratory forces by employing a rotating shaft with a mass whose centre of mass is moved from the shaft's centre of rotation. The force can be generated by either a circular or a rectilinear motion. In practice, eccentric mass shakers have rarely been used to apply loads in the vertical direction. The vibrator machine can be operated at various frequencies by adjusting the rotational speed of the shaft. To obtain good results, adequate shaft speed control is required. Additionally, Zwolski & Bien used the inverter powers of the rotating eccentric mass exciter to enable excellent control of the rotational speed and excitation frequency (Zwolski & Bień, 2011). The rotating eccentric mass (REM) exciter frequency can be controlled with a resolution of 0.006 Hz, depending on the type of inverter used. Other forced vibration tests conducted at the Bosporus suspension bridge were only partially successful since the exciters were unable to produce sufficient force at frequencies lower than 1 Hz, which is the frequency range of interest for suspension bridges (< 1 Hz) (Brownjohn et al., 2014). In short, eccentric mass shakers are not suitable for the large bridge structures such as suspensions and cable-stayed bridges where they require excitation from heavy excitation equipment.

Consequently, servo-hydraulic shakers are presented as a solution since it can deliver wide-band stimulation over most frequency ranges of preference. For the purpose of verifying design assumptions, a long wooden footbridge was excited by a servo-hydraulic vibrator with a peak pressure amplitude of + 5 kN at frequencies > 2.3 Hz (Gentile & Saisi, 2011). In general, servo-hydraulic shakers can produce larger force levels but struggle to produce excitations at frequencies exceeding 100 Hz. Nevertheless, electrodynamic shakers struggle to create force at lower levels and have difficulties with lower frequency excitations. An electrodynamic shaker was used to execute a dynamic assessment on a steel bridge in Virginia, USA (Chang et al., 2001). For this reason, only the first two modes of vibration were detected; higher modes with inherent frequencies above 7.5 Hz are immune to excitations caused by pedestrian traffic. Shakers of every variety necessitate extensive support structures, including cooling systems, control hardware, and power supplies that are usually expensive and hard to relocate. Accordingly, Table 1 illustrates the advantages and disadvantages of FVT.

### 2.2 Ambient Vibration Test

Other techniques for MI have been developed by utilising natural excitation from natural resources such as wind, waves, car or pedestrian activity, or any other service loading, particularly for large structural bridge applications. Since the equipment for forced excitation becomes extremely heavy and expensive to excite large bridge structures, ambient excitation eliminates the need for mechanical excitation devices. Gentile and Saisi used an ambient vibration-based approach to examine the structural status and damage scenario of the historic masonry bell tower, which is located next to the Cathedral of Monza (a town about 20 kms from Milan, Italy). The dynamic-based evaluation includes both theoretical and experimental modal analysis (Gentile & Saisi, 2007). For the experimental testing setup, the type and characteristics of the equipment employed have a significant impact on the effectiveness of ambient vibration measurements. A suitable selection of accelerometers and digitizers is crucial from this perspective. The type of sensor to use, such as a strain gauge, accelerometer, thermometer, or data acquisition system, should be determined by the purpose of the test; these tests include characterising physical and chemical parameters of materials, such as temperature, cracks, humidity, pH value, and corrosion, and mechanical parameters, such as ambient temperature, wind, load condition, static and dynamic characteristics (Pardi & Thogersen, 2002). The installation of the sensor type is influenced by the monitoring objective, cost constraints, and structural characteristics, as illustrated in Table 2.

**Table 2** Sensor type based on physical quantities

| Physical quantity | Sensor |
|---|---|
| Displacement | Linear variable different transformer (LVDT)<br>Long-gauge fibre optics<br>Optical<br>Laser |
| Acceleration | Piezoelectric accelerometer<br>Capacitive accelerometer<br>Forced-balanced accelerometer<br>Seismometer<br>MEMS |
| Force | Electrical resistance load cells<br>Piezoelectric load cells |
| Temperature | Electrical resistance thermometers<br>Thermocouples<br>Thermistors<br>Fibre optics-based sensors |

Sensor types such as seismometers and accelerometers have been employed in most previous studies on the full scale of ambient vibration techniques. The following criteria must be satisfied by the accelerometers: (i) frequency bandwidth DC—50 Hz; (ii) extremely low peak-to-peak noise (if practicable, less than 2 micro-g); (iii) high sensitivity (at least 1 V/g); and (iv) low full-scale range (+/0.5 g, lower or configurable) (Cunha et al., 2012). Eighteen uniaxial piezoelectric accelerometers with a 10 V/g sensitivity and a ± 0.5 g peak were used to determine the dynamic characteristics, such as natural frequencies, mode shapes, and damping ratios, of the Paderno iron arch bridge (Gentile & Saisi, 2011). The most significant mode shapes and associated natural frequencies were determined in the frequency range from 0–10 Hz and were successfully drawn from the study. In another study (Chang et al., 2001), ambient vibration testing (AVT) on a long-span cable bridge in Hong Kong was conducted in March 1997 after the surfacing paving work on the bridge deck. Nineteen accelerometers, 1 anemometer, a 24-channel data acquisition system, and triaxial signal cables were used for the measurements. This means that a typical ambient or free vibration bridge testing system usually consists of the following: (i) a set of sensors, typically accelerometers and seismometers; (ii) a data acquisition system (an analogue to digital converter) capable of digitising the analogue signal; and (iii) one computer coordinating the data, as illustrated in Fig. 4.

These tests involve measuring the structural response under ambient excitation with one or more stationary reference sensors and a collection of roaming sensors at various measurement sites along the structure in different setups. The number of points utilised is determined by the spatial resolution required to accurately characterise the form of the most significant modes of vibration (based on preliminary FE modelling), while the reference points must be sufficiently far from the corresponding nodal points. The 750 m deck length of the long-span cable bridge, Hong Kong, has been separated into seven measurement sections with 53 m intervals, as shown in Fig. 5. For each measurement, two points were located opposite each other at the two edges of the cross-section on the upper bridge deck with a sampling frequency of 50 Hz. The measurement point setup was verified on the mode shape obtained from the previous FE analysis to obtain the first 30 natural frequencies at most of the measurement locations (Chang et al., 2001). Bayraktar et al. collected the structural responses at sufficient locations on the steel footbridge deck in the vertical, lateral,

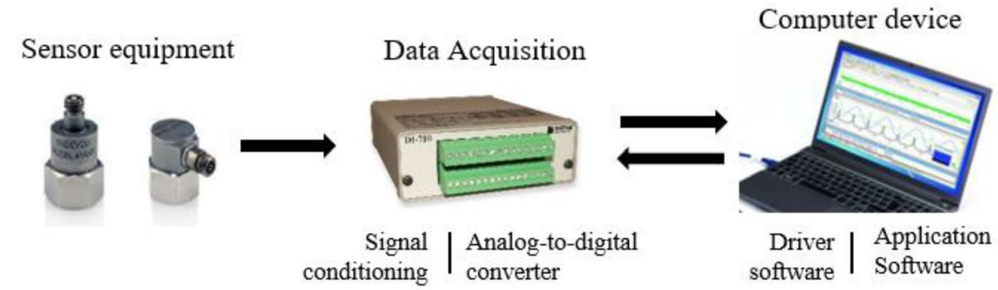
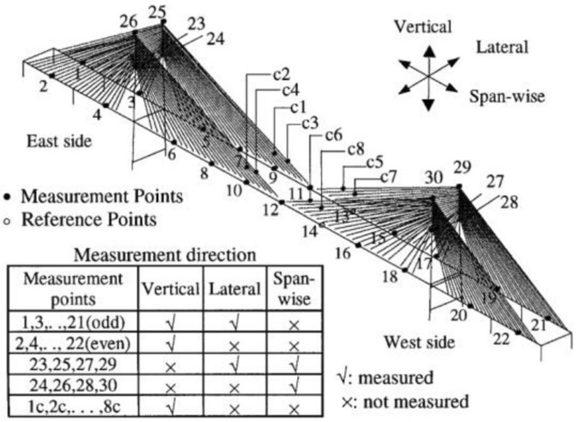


**Fig. 4** Ambient vibration test system



Measurement direction

| Measurement points | Vertical | Lateral | Span-wise |
|---|---|---|---|
| 1,3,. .,21(odd) | √ | √ | × |
| 2,4,. ., 22(even) | √ | × | × |
| 23,25,27,29 | × | √ | √ |
| 24,26,28,30 | × | × | √ |
| 1c,2c,. . . ,8c | √ | × | × |

√: measured
×: not measured

**Fig. 5** Measurement locations of the long-span cable-stayed bridge with the 3D schematic view (Chang et al., 2001)

and transversal directions from a 3D linear elastic FE model for the measurement point selection setup (Bayraktar et al., 2010). Hence, the number of measurement points used and measurement setup is critical for obtaining the modal characteristics of structures by AVT.

However, in some situations, a significant number of measurement locations are necessary, or access to these places is restricted, as may be the case when dealing with the indirect evaluation of cable forces in cable-stayed bridges or cable constructions. In this case, the employment of noncontact measuring equipment may be of high interest. A noncontact system is a measurement with absolutely no contact or probing. It is normally used for high sampling rates and measuring soft, deformable, and sensitive work pieces. Compared to contact mechanical devices, noncontact equipment is used especially when dealing with dozens of features or multiple axes, where it can measure more points, patterns, and axes in a single setup with less time taken. Noncontact systems are primarily based on laser technology, radar technology, Global Positioning System (GPS) technology, video technology, and digital photographs(EnChen & Petro, 1999; Green & Cebon, 1993a; Jo et al., 2011; Lee et al., 2017). However, some previous studies have found that the combination of these technologies could enhance the performance of measurement systems (Lee et al., 2017).

Noncontact remote sensing based on lasers is used for collecting vibration data up to several hundred feet distances, where it is very precise with accuracies between 0.1 mm and 0.22 mm. Compared to mount contact sensors, laser technology can quickly and easily predict tension levels but has a high installation cost. The I-470 Vietnam Veteran Memorial Bridge, USA, used laser technology to more easily determine the vibration under ambient forces for the long span of the bridge (EnChen & Petro, 1999). This technology provides good performance over long distances even during bad weather conditions. Recently, GPS technology has been used to measure the displacement of structures, especially large span bridges. However, GPS systems have several disadvantages, including high cost and limited precision, which usually range between 5 and 10 mm; nevertheless, the use of local stations can improve the performance with 0.2 mm accuracies (Jo et al., 2011). The combination of GPS receivers and a triaxial accelerometer could obtain coordinate time series and acceleration measurements for vibration frequencies and amplitudes. These measurements were compared to the FE model of a bridge for validation purposes. The results obtained show that the measurement from integrated GPS and accelerometer systems can be used to extract the structural dynamics accurately and detect the structural deformation within a few millimetres.

In conclusion, the benefits and drawbacks of AVT are summarised in Table 3 based on the literature study carried out for this paper. It was more practical to conduct the AVT than the FVT since it could be performed throughout traffic operations, required no costly excitation equipment, yielded reliable data, and had a lower total cost of experimental work.

**Table 3** Summarisation of the advantages and limitations of the ambient vibration testing

| **Ambient vibration test** | |
|---|---|
| Advantages | Limitations |
| 1. A convenient method for measuring the structure under service loading<br>2. No special excitation devices are required<br>3. Robust data<br>4. Non-destructive testing<br>5. The cost of the overall experiment is reduced<br>6. Can be performed during the normal operation of the structure<br>7. Practical for large and heavy structure use | 1. Tedious setup, using many hundreds of metres of electric cables<br>2.Tough and shielded. Need to ensure minimal signal loss and interference over large distances<br>3. Estimated damping values are prone to errors<br>4. High-sensitivity sensors are required |

Recent developments in dynamic testing technologies can be found in (Dilena & Morassi, 2011; Ji & Zhang, 2012). As shown in Fig. 6, AVT has received the most attention in prior studies concerning dynamic testing from 1991–2021. In general, FVT offers more accurate MI findings than AVT since the MI method uses well-defined and known input excitations, which can be adjusted to improve the response of the vibration modes of interest. However, providing regulated excitation for a considerable response in large and flexible bridges, such as suspension and cable-stayed bridges or bridges with numerous spans, is difficult and costly. In such circumstances, ambient testing is preferred since it is easier, cost-effective, and simple. Table 4 tabulated the application of dynamic testing in bridge monitoring around the world from year 1993 to 2022.

## 3 Modal Identification

The ideas of experimental estimation and structural identification of modal parameters have presented novel methods for studying vibrations, optimising designs, and gauging a structure's performance and health in recent decades. Modal identification (MI) has not only been acknowledged in mechanical and aeronautical engineering but also has identified significant applications for civil and architectural structures, biomechanical issues, space structures, and acoustical systems. MI is the study of a system's dynamic nature that is defined independently of the loads (excitation) given to the system and the system's response. Frequency-domain and time-domain approaches are used to analyse forced and in-operation vibration data.

### 3.1 Frequency-Domain Method

Modal characteristics such as frequency, mode shape, and damping are frequently used in frequency-domain approaches for vibration-based SHM (Brownjohn et al., 2014; Cunha et al., 2012; Gentile & Saisi, 2007; Pardi & Thogersen, 2002; Zwolski & Bień, 2011). In addition, certain factors associated with the Frequency Response Function (FRF) have gained widespread acceptance. Frequency-domain methods have a broad spectrum of applications than time-domain or hybrid time–frequency domain approaches due to the stability of frequency-domain structural features.

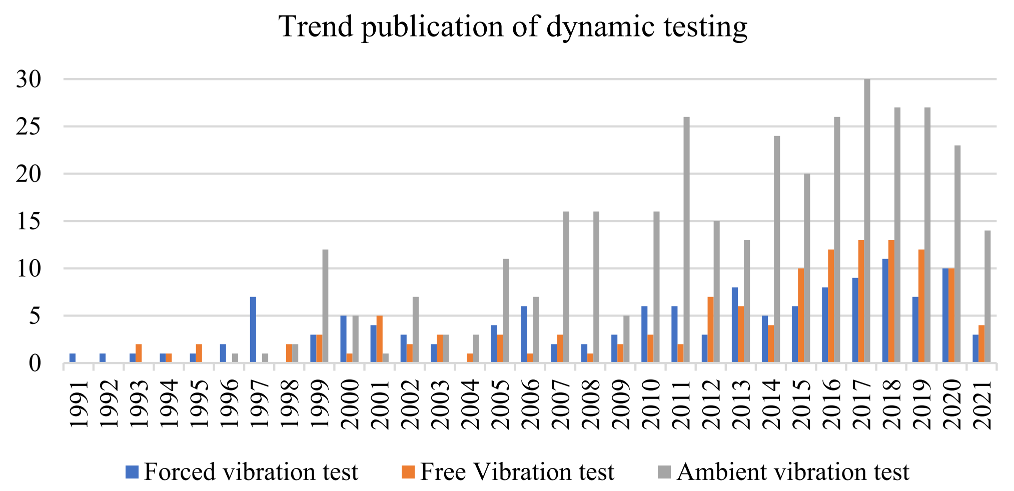


**Fig. 6** Trend publication for dynamic testing from 1991–2021

**Table 4** Application of dynamic testing in bridge monitoring

| **Testing** | | **Excitation** | **Sensor** | **Dynamic parameter** | **Application** | **References** |
|---|---|---|---|---|---|---|
| **FVT** | **AVT** | | | | | |
| ✓ | | Impact hammer | Accelerometer | Natural frequencies, damping ratios, and mode shapes | Steel Footbridge | Bayraktar and Şahin, (2014) |
| ✓ | ✓ | Rotational eccentric mass exciter, freight trains | Accelerometer and LVDT | Natural frequencies | Concrete bridge | Zwolski and Bień, (2011) |
| ✓ | ✓ | Suspension mass 60 tonne, ambient load | Triaxial accelerograph | Frequencies, mode shapes, and damping ratio | Cable-stayed bridge | Lee et al., (2017) |
| | ✓ | Light vehicles crossing the spans and wind | Triaxial force-balance accelerometers | Frequencies, mode shapes, damping ratio | 256-m arch long-span steel bridge | Jo et al., (2011) |
| | ✓ | Pedestrian load | Piezoelectric accelerometers | Damping | Long and slender footbridge | Green and Cebon, (1993a) |
| ✓ | | Shaker | Piezoelectric accelerometers | Frequencies, mode shapes, damping factors | 64 m of the reinforced concrete bridge | Dilena and Morassi, (2011) |
| | ✓ | Wind speed | Triaxial accelerometers GPs sensor | Natural frequencies and mode shape | 2460 m span large-cable-stayed bridge | Magalhães et al., (2012b) |
| | ✓ | Running car with constant speed | Hybrid video cameras | Natural frequencies | Long suspension bridge | Nishimura et al., (2012) |
| | ✓ | Traffic and wind | Seismometer and GPS | Natural frequencies | 391.25-m steel bridge | Green and Cebon, (1993b) |
| ✓ | ✓ | Impulse excitation (shock loads) and passing trains | Piezoceramic low frequency | Mode shapes, frequencies, damping ratios, and maximum amplitudes | Railway steel continuous truss bridge | Kilikevičius et al., (2018) |

In this context, there are a wide range of input–output MI methods whose application is based on either estimation of a collection of frequency response function (FRF) or the corresponding impulse response functions (IRFs) derived using a fast Fourier transform (FFT) method. The FRF measures how well the output response of a structure matches the applied force. The fast Fourier transform (FFT) algorithm, available in any signal handling analyser and computer software package, is then used to transfer the structure's output response or observed time data (displacement, velocity, and acceleration) from the time domain to the frequency domain. The FFT algorithm was developed by James Cooly and John in 1965 and introduced the use of experimental approaches in structural dynamics (Peeters et al., 1998). Modal analysis theory contributes to the establishment of the link between measured FRFs and the modal data of the structure under test. The goal of the research was to determine modal data from measured FRF signals. Dynamic features of bolt constructions were analysed by Sulaiman et al. (Sulaiman et al., 2016) utilising the frequency response function (FRF) to detect deterioration in a bolted joined structure. The proposed EMA method using FRF data has been exhibited to effectively and precisely diagnose degradation in structure.

By collecting data from accelerometers over time and transforming it to the frequency domain using the FFT (Fig. 7), Aulakh et al. (Aulakh & Bhalla, 2021) attempt to establish the modal parameters, including frequency and mode shape, of a steel beam. Four of the possible mode forms were evaluated for use in damage inspection and detection. When the frequency of the stimulation is the same as one of the inherent frequencies of the system, certain deformation patterns will emerge. Large vibration responses, which can be uncomfortable or even damaging, are generated by pressures activating the material at resonant frequencies due to the modes, which

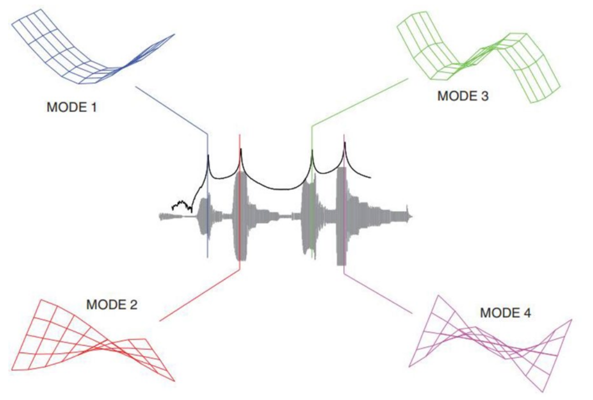


**Fig. 7** Mode shape identification using FFT (Aulakh & Bhalla, 2021)

are inherent features of the structure. Identifying and analysing modal characteristics regularly can help with the evaluation of structural functionality and durability (Fig. 8).

In short, the most typical data used for parameter extraction are frequency response functions (FRFs), which use excitation input and the corresponding output of the structure. Over the subsequent few decades, the collection of FRFs followed by modal parameter identification based on FRF models proved to be the dominant approach. The FRFs were measured first, followed by parameter identification of the modal frequencies, damping factors, and mode shapes.

### *3.1.1 Peak Picking Method*

Peak picking (PP) is the simplest and fastest methodology to measure modal parameters in the frequency–time domain (Ventura, 2001). This method has been utilised for a variety of purposes over the years. PP is based on the concept that when a structure is exposed to ambient excitations, it will exhibit significant reactions around its natural frequencies. The peaks in the PSDs computed for the time histories collected at the measurement sites can be used to identify these frequencies. In this method, the natural frequencies are determined as the peaks of the averaged normalised power spectral densities (ANPSDs), in which the natural frequencies are directly obtained from the PSD plot at the peak. Fig. 8 shows the frequency spectrum of all possible modes, with the 1.66 Hz peak representing the first mode shape and the following peak representing the next mode shape (Felber, 1994).

One practical implementation of this method was developed by Felber. The research developed a unique approach based on this concept to speed up the MI of ambient vibration data, and this foundational work served as the inspiration for the creation of interactive ways to implement the PP technique quickly and efficiently. When the modes of a system are well separated, the PP approach has proven to be effective in MI. This approach is straightforward to apply, but the results produced may be manipulative if a system has closely spaced modes (Wang et al., 2016). However, due to the reliance on PSD spectrum resolution, this approach is not appropriate for large and complicated structures, resulting in erroneous results. Hence, the application of a new frequency-domain technique called frequency-domain decomposition (FDD) was introduced to solve this problem.

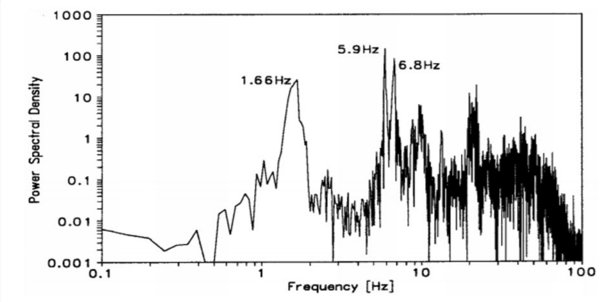


**Fig. 8** ANPSD for the Colquitz River bridge (Felber, 1994*)*

### *3.1.2 Frequency-Domain Decomposition (FDD)*

In Prevosto studies, the limitation of the simple PP frequency-domain method was enhanced and overcome by using a single-value decomposition of the matrix of response spectra in producing PSDs for a set of SDOF systems (Prevosto, 1982). This method was then implemented by Brincker et al. to develop the new algorithm of the frequency-domain method, which is known as frequency-domain decomposition (FDD) (Brincker et al., 2000). Frequency-domain techniques, which can be nonparametric or parametric, begin by constructing output spectrum or half-spectrum matrices from measured dynamic responses. A nonparametric FDD is a simple, straightforward, and user-friendly approach for separating modes that are closely spaced. The modes are chosen by simply finding the peaks in the singular value decomposition (SVD) plots based on the power spectral density of the response. Furthermore, the various types of modes may be distinguished, especially in the case of closed modes. Automated identification based on the FDD method is recommended due to its simplicity and efficiency and hence can decrease human intervention in identification, which offers better and more efficient modal estimation. However, the precision of the estimated natural frequency is restricted by the FFT resolution since this FDD approach is based on a single frequency line from a FFT analysis, and hence no modal damping is computed.

### *3.1.3 Enhanced Frequency-Domain Decomposition (EFDD)*

As a result, a new approach called enhanced frequency-domain decomposition (EFDD) was developed to show superior modal data with the required modal damping ratio estimations (Brincker et al., 2001). EFDD is an extension of the FDD method, where it is able to integrate damping and gives a better estimation of both natural frequencies and mode shapes. In this method, the SDOF power spectral density function is identified around a resonance peak and inverted to the time domain using the inverse discrete Fourier transform in EFDD. The natural frequency is calculated by calculating the number of zero-crossings as a function of time, and the damping is calculated by calculating the logarithmic decrement of the related SDOF normalised autocorrelation equation. The SDOF function is computed based on the shape of the previous FDD PP (Jacobsen et al., 2006). Numerous studies have investigated the structural behaviour of bridges using this frequency-domain method in operational modal analyses methods, as shown in Jeary and Sparks (1977); Materazzi & Ubertini, 2011; Ghalishooyan & Shooshtari, 2015; Lennart, 1999) A scaled reinforced concrete box girder's dynamic behaviour was investigated by using the EFDD method in OMA, where the first natural frequencies, 25 Hz, and damping ratios in the range of 1–5% obtained show good agreement with values in the literature (Altunişik et al., 2012). Overall, EFDD is an extension of the FDD method, which is a basic method that is extremely easy and simple to use, fast processing method, high accuracy, and efficiency in identifying higher-order modes of bridge structural behaviour.

## 3.2 Time-Domain Method

The time-domain methodology relies on a single degree of freedom (SDOF) to perform calculations. The SVD of the output correlation matrix is used to extract the undamped mode forms concerning the sensor positions. The PP approach is then used to extract the natural frequencies and damping ratios from the SDOF signal, after the retrieval of the mode shapes. Several distinct algorithms are applied in this technique.

### *3.2.1 Natural Excitation Technique (NExT)*

The modal system identification software's NExT method was utilised initially (James et al., 1995). The preamble NExT method refers to the natural excitation method, which generates IRFs using cross-spectra of ambient vibration response rather than FVT. This technique was first used for EMA and later for OMA for structures subjected to natural excitation. NExT acquires a structural response as a result of environmental stimulation at various locations. Next, the correlation function is calculated using the time histories of the recorded data. The correlation function is widely used to study systems that are subjected to ambient excitation. NExT can be characterised as an OMA technique when combined with any multi-input multi-output (MIMO) time-domain algorithm, such as the extended Ibrahim time-domain (EITD) method (Fukuzono, 1986), the ERA (Juang & Pappa, 1985), and the polyreference complex exponential (PRCE) technique (Vold et al., 1982). The results of three techniques, the natural excitation technique, ERA, and poly-least squares frequency-domain method are compared among themselves and with those of a Humber bridge test in 1985, revealing few significant modal parameter changes over 23 years in cases where direct comparison is possible (Brownjohn et al., 2010). When utilising NExT for modal parameter estimation, it is important to note that the data in OMA are stochastic, whereas NExT approaches have a deterministic framework (Ghalishooyan & Shooshtari, 2015).

### *3.2.2 Autoregression Moving Average (ARMA)*

Another technique in the time-domain OMA method using an autoregression moving average (ARMA) was performed. ARMA models can forecast a time series of current values based on previous values and a prediction error. The ARMA model may be used to explain linear systems. The ARMA model is an extended model of a linear time-invariant system stimulated by white noise, with the measured response assumed to be stationary. When there are numerous input excitations, vector ARMA or autoregressive moving average vector (ARMAV) models are utilised (Rainieri & Fabbrocino, 2008). The prediction error method (PEM), which minimises the estimating loss, was first proposed to derive modal parameters based on the ARMA model (difference between the response estimated by the model and the measured response) (Lennart, 1999). In (Jacobsen et al., 2006), the ARMA model was used as an application in modal analysis and was characterised as a time-domain modal analysis technique that can be used for the identification of modal parameters in operating conditions. Moreover, Ghalishooyan & Shooshtari found that the ARMA approach is not recommended for OMA since it is computationally demanding and does not always converge in all cases. (Ghalishooyan & Shooshtari, 2015) Other ARMA approaches include instrumental variable (IV), linear multistage (LMS), and two-stage least squares (2SLS) methods, which require considerable computing power (Petsounis & Fassois, 2001). ARMA methods were formerly widely employed in civil engineering constructions, but their popularity has decreased because of the significant computing time required (Bodeux & Golinval, 2001).

### *3.2.3 Stochastic Subspace Identification (SSI)*

An alternative method that was more stable in the time-domain OMA technique based on a stochastic subspace was then suggested. This method, first developed in 1991 by Van Overschee and De Moor, determines the system's spatial state directly from the measured data. (Moor et al., 1990). It significantly decreases computing complexity when compared to other approaches such as ARMAV (Rainieri & Fabbrocino, 2008). There are two types of algorithms in stochastic subspace identification (SSI) classifications (Peeters & Roeck, 1999); covariance-driven SSI (Cov-SSI) and data-driven SSI (DD-SSI). The SVD is utilised in Cov-SSI to minimise the noise in deterministic system identification (Kung, 1978). DD-SSI correlation data are used to create a block Hankel matrix, as opposed to the FRF used in EMA techniques. DD-SSI can be implemented using the canonical variant analysis (CVA) technique, the unweighted principal component (UPC) approach, or the principal component (PC) method, in which the covariance Hankel matrix is first weighed and then decomposed using the SVD process (Overshee & Moor, 2012). The matrix is weighed using PC, CVA, or UPC techniques. The covariance-driven and data-driven methods have their own set of distinctions. The covariances in the SSI-COV technique may be calculated very quickly using the FFT algorithm (Reynders et al., 2016). SSI-COV and SSI-DATA can both estimate system modes and forced oscillations, but SSI-COV is better at precisely estimating damping ratios than SSI-DATA (Farrokhifard et al., 2019).

Tables 5 and 6 contain an overview and examples of the use of the aforementioned OMA methodologies in previous research, respectively. Overall, the SSI method has the merits of high-efficiency computing and high-accuracy parameter estimation as opposed to other OMA approaches. As a result of SSI's adoption as a common OMA strategy, its derivative, SSI-COV, is also extensively applied. The MAC value can be increased to above 90% using the SSI approach, as has been revealed by previous studies.

## 4 Vibration-Based Structural Health Monitoring

Extensive studies on SHM systems, which are based on vibration measurements obtained from bridge structures, are used to detect changes in dynamic characteristic parameters such as the natural frequency, modal strain energy, mode form curvature, and dynamic flexibility (Sakai & Unjoh, 2007). A decrease in natural frequencies represents structural degradation or damage caused by an extreme event, resulting in a stiffness reduction (Ni et al., 2008). Natural frequencies have been identified as one of the most remarkable indicators among the dynamic characteristic parameters from vibration-based SHM systems when detecting damage in a structure (Sakai & Unjoh, 2007). Numerous studies involving the use of natural frequency parameters in the development and application of vibration-based damage detection techniques for bridge structures have been reported since 1979. Gentile et al. investigated the dynamic characteristics of the Paderno iron arch bridge by determining the vertical and horizontal natural frequencies using periodic dynamic tests to evaluate the bridge structure condition (Gentile & Saisi, 2011). This study determined that the resonant frequency of the first bending mode decreased slightly on the second AVT, revealing possible deterioration in the structural condition or the occurrence of damage. On the basis of that principle, the damage is defined as changes in bridge structural characteristics parameters such as dynamic characteristics presented into a structural system that have an unfavourable impact on the structural integrity of the system, including changes in structural mass, damping, and stiffness. A comprehensive study or procedure is needed for damage detection and deterioration severity assessment, as dynamic testing and modal identification are unable to deliver (Fig. 9). Hence, this section examines the required extensive research.

### 4.1 Natural Frequency

One of the earliest vibration-based SHM tests used to study the changes in the dynamic properties was performed on an existing prestressed concrete bridge to study the change in vibrational characteristics caused by bridge deterioration during failure testing (Kato & Shimada, 1986). This study used a variety of dynamic

**Table 5** Summary of available OMA techniques

| Method | Type | Advantages | Limitation |
|---|---|---|---|
| PP | Frequency domain | The simplest, most straightforward, and least computationally expensive approach | Inaccurate for a system with closely spaced modes, as in most of the cases in real structures |
| FDD | Frequency-domain | Natural frequencies and closely spaced mode shapes can be accurately identified | The precision of the estimated natural frequency is restricted by the FFT resolution<br>Damping ratios cannot be calculated |
| EFDD | Frequency-domain | Method of processing that is simple to use and quick<br>Can determine damping ratios, mode shapes, and natural frequencies more accurately than FDD | Exact estimation of modal damping remains a challenge, which may often lead to biased estimates |
| NExT | Time-domain | Provides a solid foundation for extending EMA methods in OMA | The nature of the data in OMA is stochastic, but the framework in NExT techniques is deterministic |
| ARMA | Time-domain | Output measurements can be used directly | A computationally demanding method |
| SSI | Time-domain | High level of parameter estimate accuracy as well as a high level of computing efficiency compared to other OMA techniques | A mathematically complex method |

**Table 6** Summary of OMA applications for bridge monitoring

| Application | OMA method(s) | Result | References |
|---|---|---|---|
| Scaled reinforced box girder concrete bridge model | EFDD and SSI | The natural frequencies and mode shapes obtained from all measurements using EFDD and SSI methods are similar to each other. The modal assurance criterion (MAC) values for both EFDD and SSI are between 90–100% | Altunişik et al., (2012) |
| Long cable-stayed bridge | P-LSCF, ERA/NExT, and SSI-COV | There are no systematic differences between frequency values for all three techniques. Among the three techniques, SSI-COV appears to be the most effective of the three methods at detecting all modes (with one possible exception). The next best approach is NExT/ERA, although the damping estimates are the highest of the techniques | Brownjohn et al., (2010) |
| Long-span concrete arch bridge | FDD | Enabling the tracking of the bridge's first 12 natural frequencies | Magalhães et al., (2008) |
| Arch bridge | Peak picking and SSI | Natural frequencies obtained from modal analysis were used for updating the FE model. The differences between the natural frequencies are reduced from 27 to 3% | Bayraktar et al., (2009) |
| Integral abutment highway bridge | Peak picking, FDD, and SSI | The mode shapes acquired using SSI were judged to be of better quality than those produced through FDD | Whelan et al., (2009) |
| Double-deck steel-arch bridge | Peak picking | Natural frequencies recorded from the modal analysis have changed significantly, with a minor tendency to increase after bridge rehabilitation | Costa et al., (2014) |
| 125 m long with three spans concrete deck bridge | EFDD | MI was used to update the FE model, and the result obtained was used to evaluate the bridge's seismic performance in line with the 2015 Canadian Highway Bridge Design Code | Feng et al., (2016) |
| FRP (fibre-reinforced polymer) bridges | Eigensystem realisation algorithm (ERA) | Results of the MI give useful information about the dynamic characteristics of structures | Casalegno and Russo, (2017) |
| Cable-stayed bridge | SSI-COV | Accurate and robust MI results are obtained when the automated OMA algorithm is applied to a cable-stayed bridge structure | Sun et al., (2017) |
| An 11-span concrete bridge | Peak picking, FDD and SSI-DD | The PP technique was the most effective in terms of discovering the largest number of frequencies, while the SSI method produced the best quality mode shapes | Chen et al., (2017) |
| SHM of the pedestrian bridge | FDD | A good agreement was found between the FE method and system identification results | Ali et al., (2019) |

test methods to provide a comparison and evaluation of the various vibration-response methods. From this study, an evaluation of acoustic emission sensor data detected rapid critical crack growth in one girder, indicating great potential for monitoring structural deterioration under dynamic service loads. The main objective of this study was to investigate damage detection using dynamic properties. The natural frequency of the first vertical mode was discovered to rapidly decrease as the static loading cycles applied at the span's centre increased to the ultimate load. The other observations on the prestressed concrete bridge were carried out in Huth et al. (2005). Large-scale tests with incremental damage were performed on a prestressed concrete highway bridge to

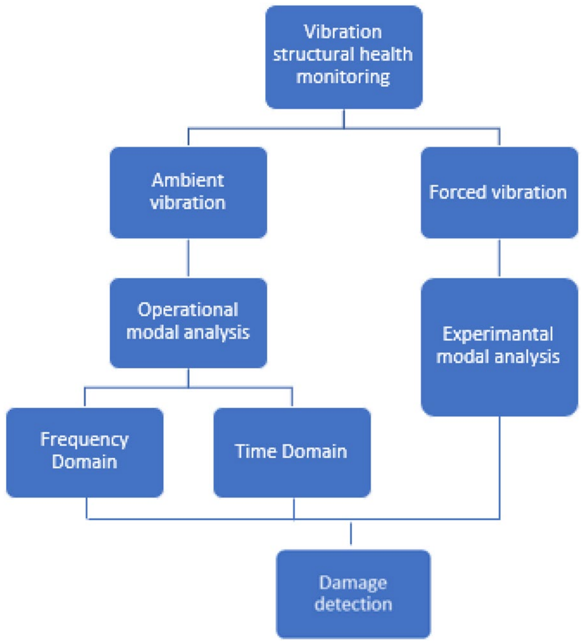


**Fig. 9** Summarisation of vibration-based structural health monitoring

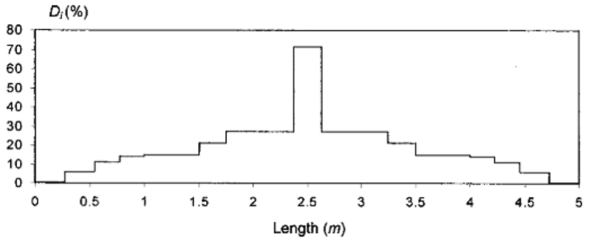


**Fig. 10** Distribution of damage index along bridge deck (Brownjohn et al., 2001)

detect and quantify damage based on changes in natural frequencies and mode shapes. Dynamic measurements have proven that changes in dynamic characteristics can be used to detect any damage under early conditions. From the research, it was concluded that the differences in resonant frequency are related to the damage coefficient. However, the natural frequencies itself was not able to quantify the severity and location of damage to the structure.

### 4.2 Damage and Stiffness Reduce Detection by Using the FE Model

Damage to structures can be identified using an experimental modal identification technique and a FE model updating method (Brownjohn et al., 2001; Lu et al., 2012). The damage evaluation approach is conducted in two update phases. The first stage involves using vibration data collected from the unharmed structure to calibrate the initial finite element model to a reference state of the structure. The second stage involves revising the original FE model to generate one that is capable of accurately reproducing the vibration data acquired during the damaged condition. It is useful to track the damage by contrasting the original FE model with the corrupted one. Reinforced concrete structures are good examples of the types of structures that can benefit from this technique because the damage pattern in these types of structures is represented by a drop in element bending stiffness. The effects of damage in these buildings are typically dispersed over larger areas. It is necessary to determine the entirety of the region that will suffer a loss in bending stiffness as a result of the applied damage. The FE model of the damaged reinforced concrete bridge deck reported was thoroughly pre-validated and post-validated with dynamically measured data from the intact and affected structure(Chang et al., 2001; Xia & Brownjohn, 2004). It has been determined through post-validation of the FE model for the damaged structure that it has a lower moment of inertia than the undamaged structure. The severity of damage in the structure can also be determined based on the stiffness distribution of the compromised structure. The cross-section with a lower rigidity pinpointed the damage in the beam. A damage index Di reflecting the level of damage is stated as in Eq. (1):

$$D_i = \frac{\Delta(EI)}{(EI)_0} \times 100\%, \tag{1}$$

where Δ(EI) refers to the variation in rigidity between the original and compromised beam's cross-section; and $(\mathrm{EI})_0$ indicates the beam's undamaged cross section's initial rigidity. The damage was severest near the beam's midspan, where 71% of the beam was destroyed (Fig. 10). This result demonstrated that the stiffness values can be updated utilising the measured responses before and after damage. Previous visual inspection and strain measurements were found to correlate well with the locations and degrees of stiffness loss seen in the bridge.

Moreover, Soyoz et al. expanded their research to a three-span continuous prestressed box girder bridge in Irvine, California, USA (Soyoz & Feng, 2009). An identical SHM system was employed throughout the research. The structural stiffnesses of the bridge were suitably updated based on vibration measurements performed at the bridge over five years. Fig. 11 shows the trend in superstructure stiffness values over 5 years, where the observed drop in stiffness value is not attributable to prestress loss but due to material deterioration throughout the monitoring period. Analysis indicates that the

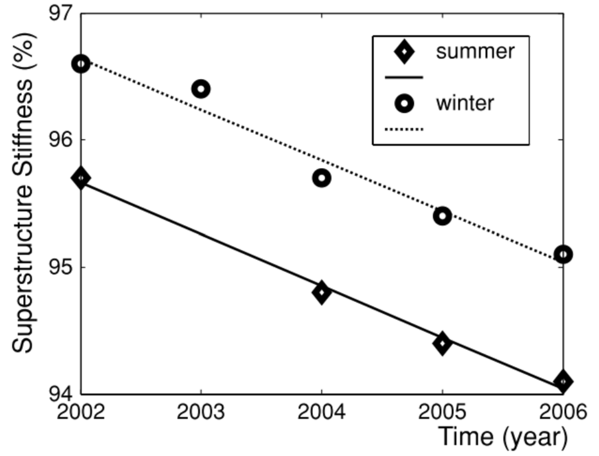


**Fig. 11** Trend in superstructure stiffness values (Soyoz & Feng, 2009)

first modal frequency and the superstructure stiffness both decreased by 5% after damping the structure. This research is the first step toward formulating an analytical instrument for evaluating the state of a bridge's superstructure via changes in stiffness, which is in turn linked to variations in natural frequency.

Lu et al. assessed the load-carrying capacity of the Jianninxia Bridge by analysing the dynamic strain response curves at various speeds subjected to extra traffic impact values (Lu et al., 2012). The result from AVT indicates that the bridge's overall rigidity complies with the design requirements, as the actual natural frequency measurement is greater than the theoretical value, indicating that the bridge is in a safe condition. Xia & Brownjohn discovered that the damage location and quantification of the damaged structure can lead to the measurement of residual stiffness and load-carrying capacity (Xia & Brownjohn, 2004). From their findings, the bridge load-carrying capacity assessment cannot be estimated directly after data analysis but requires the development of the relationships between the moment of inertia with the steel ratio and the ultimate moment in the RC structure.

Table 7 presents a summary of the assessment of the structural health based on vibrations. After the finite element (FE) model of the damaged structure has been rigorously validated by dynamics-based model updating approaches, it is possible to quantitatively assess the structural status of a damaged forced concrete bridge deck. This includes the residual stiffness, residual stiffness, and load-carrying capacities of the structure. When evaluating a reinforced concrete structure's ability to support a load, it's imperative to construct a relationship between the moment of inertia and both the steel ratio and the ultimate moment. Thus, it is necessary to obtain a credible initial FE model by determining additional uncertainties, including the structure's boundary conditions, before damage diagnosis. Furthermore, damages are located by adjusting the parameters that quantitatively simulate the model to reflect the latest data, and this is accomplished by applying the model updating technique to the initial FE model that has already been pre-validated. In conclusion, the final approved FE model can be applied to simulate the damaged structure. Nonetheless, initial cost, estimated life-cycle maintenance cost,

**Table 7** Vibration-based structural health monitoring assessment

| Application | Assessment | Method | Author |
|---|---|---|---|
| Long arch bridge | Continuous online identification of modal parameters | Implements algorithms and FE updated model | Magalhães et al., (2012a) |
| Prestressed concrete bridge | Detect and quantify the damage | Based on changes in natural frequencies and mode shapes | Huth et al., (2005) |
| Reinforced concrete bridge | Quantitative condition evaluation of a damaged | Updated FE model | Brownjohn et al., (2001) |
| Reinforced concrete bridge | Residual stiffness and load-carrying capacity | Relationships of the moment of inertia with the steel ratio and ultimate moment | Xia and Brownjohn, (2004) |
| Three-bent reinforced concrete bridge | Structural stiffnesses correlated to the structural capacity | Time-domain extended Kalman filtering (EKF), FE updated model | Soyoz and Feng, (2008) |
| Reinforced concrete structure | Changes in service life estimates | Bayesian techniques | Suo and Stewart, (2009) |
| Three-span continuous prestressed box girder bridge | Drop in the superstructure stiffness value in 5 years | Structural stiffnesses of the bridge were updated periodically for five years based on vibration measurements | Soyoz and Feng, (2009) |
| Curved steel box girder bridge | Load rating for the current structure capacity | FE models | Huang (2010) |
| Three-span prestressed concrete | Structure's performance and data for future designs | FE model's predictions | Kafle et al., (ntification from Ambi2017) |

and predicted life-cycle rehabilitation expenses, such as repair/replacement costs, loss of contents or death and injury losses, road user costs, and indirect socioeconomic losses, are required for extended assessment as it is not covered in this research. Other research (Ahmad, 2003; Faber et al., 2000; Stewart & Mullard, 2007; Suo & Stewart, 2009; Yuefei et al., 2014) offer comparable and similar in-depth analyses.

## 5 Conclusion

There have been a large number of studies of vibration-based systems over the last several decades. This state-of-the-art review paper has focused on dynamic testing techniques, MI algorithms to analyse the measured data, damage detection, and an evaluation of the load-carrying capacity based on vibration SHM. Based on a review of previous work, the following findings can be made, and the following weaknesses can be identified to further improve the SHM system for supporting long-term maintenance and rehabilitation decision-making in the field of highway bridges:

(1) AVT is the simplest of the two types of dynamic testing since the structural response may be monitored while the structure is still in use, and artificial excitation systems, which can be complicated and expensive, are not necessary. The method has the drawback that some of the predicted dynamic parameters, particularly damping, may be incorrect because their values are dependent on the (uncontrolled) unknown excitation level.
(2) FVT offers more accurate MI findings than AVT since the MI method uses well-defined and known input excitations, which can be adjusted to improve the response of the vibration modes of interest. However, this method is not suitable for use in large flexible civil structures, where extremely heavy and expensive equipment is required.
(3) EMA has been increasingly relevant in mechanical engineering for ensuring design, optimisation, and validation but less relevant for large civil construction applications because existing exciters such as impact hammers and shakers may not be sufficient for any particular force required.
(4) Overall, in comparison to other OMA techniques, including the frequency and time domains, the SSI method offers the benefits of high-accuracy parameter estimation accuracy and computational efficiency.
(5) The results from the reported tests indicate that vibration testing is a useful tool for obtaining information on the condition of structural systems, such as damage and stiffness assessment and load-carrying capacity assessment.

**Author contributions**
All authors have contributed to the work and wrote the paper. The authors confirm their contribution to the paper as follows: study conception and design: SSS, AJ, SAK. Data collection: SSS, AJ. Analysis and interpretation of results: SSS. Writing original draft: SSS. Writing review and edit: SSS, MAA, NMA. All authors read and approved the final manuscript.

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