Chapter

Introductory Chapter: Some Insights into Bridge Structural Condition Monitoring

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1. Introduction

Bridge structural condition monitoring has become a hot spot in both research and engineering fields. Bridges, serving as a connection between cliffs, shallow rivers, or special environmental conditions, have a lot of forms in functionality, economy, and art consideration. For instance, concrete bridge, steel bridges, cable stayed bridge, suspension bridges shown in **Figure 1,** and so on have been served in various cities [1]. The initial use of bridge is for functionality like footbridge [2], and then other considerations are included. As shown in **Figure 1**, both the suspension bridge and cable-stayed bridge are extending for long span and large area application in civil engineering.

Since the bridges provide the convenient transportation for passengers and vehicles, the in-service safety shall be the most essential issue in the lifecycle service of bridges, providing timely early stage warning and suggestion for the possible maintenance [3–7]. For instance, fiber optic sensors are applied for full-scale destructive bridge condition monitoring [3]. A comprehensive discussion on bridge instrumentation and monitoring for structural diagnosis is conducted in [4], expressing the general steps for bridge management system for condition monitoring including experimental tests, nondestructive tests, performance evaluation, and so on; in [5], the temperature effect is studied between the temperature and the frequency ratio for model plate-girder bridges under uncertain temperature conditions; and also the modal strain energy is extended to predict the location and severity of the damages; in [6], the acoustic emission is applied for monitoring the prestressed concrete bridges health condition after constructing a reference-signals database; in [7], Poisson process is applied to simulate the arrival of vehicles traversing a bridge, and a stochastic model of traffic excitation on bridges is constructed to be incorporated in a Bayesian framework, to assess the properties and update the uncertainty for condition evaluation of the bridge superstructure.

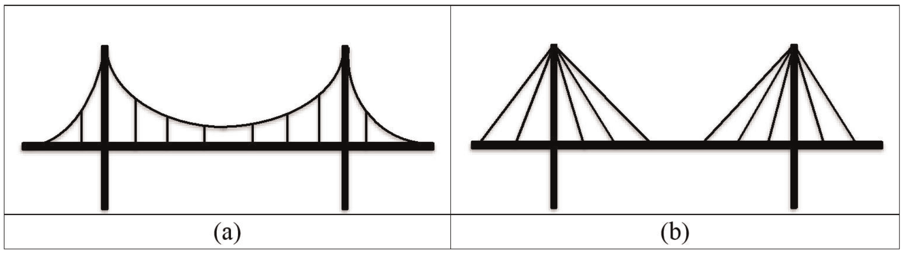

Figure 1.
Diagram for (a) suspension bridge; (b) cable-stayed bridge.

1.1 Sensing techniques

Sensing techniques include a lot of conventional technologies and advanced technologies developed in recent decades. The conventional technologies include impact echo testing, dye penetration, strain gage, electrical magnetic testing, piezoelectric gages, acoustic emission, leakage testing, magnetic testing, ultrasonic testing, radiographic testing, eddy current testing, infrared thermography testing, microwave testing, and so on. Advanced technologies include phased array ultrasonic testing, eddy current array testing, microelectromechanical sensors, air-coupled sensors, vision sensors with cameras, radar sensors, and so on. In [8], the condition monitoring system for Tsing Ma Bridge is thoroughly introduced: the wind and structural health monitoring (WASHMS) in the Tsing Ma Bridge used about 300 sensors: anemometers, temperature sensors, accelerometers, strain gauges, displacement transducers, weigh-in-motion sensors, and so on. The Global Positioning System-On-Structure Instrumentation System (GPS-OSIS) was installed to improve the bridge displacement response monitoring. In [9], the Global Navigation Satellite System (GNSS): BeiDou Navigation Satellite System (BDS) and Global Positioning System (GPS) are applied to monitoring the bridge displacement responses. In [10], image processing is applied to construct a vision-based monitoring system for cable tension estimation under various weather conditions in the cable-stayed bridge, proving that the natural frequencies can be obtained up to the third and fifth modes. In [11], the radar sensor techniques were employed to predict the changes in the natural frequencies of bridge girders with certain characteristics that control the structural performance with being incorporated with computational modeling. In [12], commercially available remote sensors for Highway Bridge condition evaluation such as ground penetrating radar (GPR), optical interferometry, digital image processing (DIC), and so on are summarized.

1.2 Damage identification

Damage identification, part of structural health monitoring (SHM), has appealed lots of attention since the occurrence of defect/damage demands repairing and maintenance, simultaneously leading to economic loss. Damage identification techniques can be summarized into two categories: model based and data based, and this has been discussed in [1].

Modal testing serves as the fundamental and most essential technique in SHM, and along with the development of technology, modal testing underwent experimental modal analysis (EMA) and operational modal analysis (OMA). The key difference between them is EMA needs, while OMA does not demand the measurement of excitation. During the last decades, new measurement techniques also arise in engineering application. For instance, ultrasonic testing, eddy current, magnetic particle testing, acoustic emission, and so on are all imposed in SHM.

Comparing with the model-based techniques, data based, especially the output only based damage identification suggests a wide applicable potential since its merit relying on structural responses solely. Transmissibility is a typical output only based technique [13], which has been developed in the past decades for system identification, damage detection, localization, quantification, and assessment [14]. Review can refer to [14]. Even a lot of investigations about transmissibility can be accessed to [15–19], for instance, transmissibility coherence (TC) is raised [14, 17]; cosine-based indicator is constructed from the modal assurance criterion (MAC) and incorporated with transmissibility for damage detection and quantification relatively [15]; Mahalanobis distance is also applied to transmissibility for damage detection [16]; transmissibility is extended to apply in the responses analysis of ultrasonic testing [19]; the transmissibility still encounters difficulty in both theory development and engineering application. This study tries to extend the transmissibility theory for estimating and reconstructing mode shape from structural responses solely. Remaining work can be summarized as follows: Section 2 gives the theoretical development of transmissibility mode shape (TMS) and comparison between transmissibility-based OMA and frequency response functions (FRFs) based EMA, Section 3 gives the possible damage indicators, and Section 4 gives the numerical case study; conclusions are finally summarized.

2. Structural condition monitoring

2.1 Transmissibility and transmissibility coherence

Transmissibility has several kinds of definitions with existing reviews [14], while the fundamental concept is the ratio between two structural responses, which can be expressed as

$$T_{(i,s)} = \frac{X_i}{X_s} \tag{1}$$

where i, s mean the response locations, while X_i and X_j represent the frequency spectrum of dynamic response x_i and x_s in time domain.

Transmissibility can be assessed with several ways, for instance, to use FRFs if available,

$$T_{(i,s)} = \frac{X_i}{X_s} = \frac{H_{ir}}{H_{sr}} \tag{2}$$

where r denotes the excitation location (assuming single load). H represents the FRFs.

Similar to the application of coherence in FRFs analysis, TC is also raised and defined as

$$TC_{(i,s)} = \left| \frac{G_{is}^2}{G_{ii}G_{ss}} \right| \tag{3}$$

where G means the auto- and cross spectrum. TC is initially developed for damage/small nonlinearity detection and quantification, and later it is advanced for natural frequency extraction.

2.2 Transmissibility mode shape (TMS)

For a single load linear elastic structural system, the FRF can also be expressed as

$$H_{(i,r)}(\omega) = \sum_{p=1}^{n} \frac{\phi_p^i \phi_p^r}{k_p - \omega^2 m_p + j\omega c_p} \tag{4}$$

where p denotes the p^{th} mode, n means the number of modes considered. k_p, m_p, and c_p mean modal stiffness, mass, and damping, respectively, ϕ means the mode shape, and ω represents the frequency.

Then, the transmissibility illustrated above can be further expressed as

$$T_{(i,s)} = \frac{X_i}{X_s} = \frac{H_{ir}}{H_{sr}} = \frac{\sum_{p=1}^{n} \frac{\phi_p^i \phi_p^r}{k_p - \omega^2 m_p + j\omega c_p}}{\sum_{p=1}^{n} \frac{\phi_p^s \phi_p^r}{k_p - \omega^2 m_p + j\omega c_p}} = \frac{\phi^r}{\phi^s} \tag{5}$$

Note, this relation shall be better if obtained by using Laplace transform. As to Eq. (5), if fixing s, transmissibility will allow assessing the mode shape, or scalar mode shape. For each mode, transmissibility will express the scalar mode shape at each location, if further obtaining the direction of the scalar mode shape in each measurement location, and then the transmissibility-based mode shape TMS (full-unscaled mode shape ϕ_{1s}, ϕ_{2s}, ϕ_{3s}, ..., ϕ_{Ns}, N is the number of measured responses) will be obtained. A general definition can be denoted as

$$TMS\Big|_{(i,p)}^{B} = \int_{f_{B1}}^{f_{B2}} T_{(i,s)} df \tag{6}$$

where B denotes the frequency boundary [B1, B2] around the natural frequency, and f indicates the frequency domain. TMS_p means p^{th} TMS. All the TMSs will later contribute for further OMA [14].

2.3 Comparison between transmissibility and FRF

Table 1 illustrates the comparison between EMA and transmissibility-based OMA, and it can be found that transmissibility has been developed by analog of FRF, where transmissibility can also perform the same function as FRF, like in damage detection, system identification, and so on. Note that transmissibility has not been thoroughly investigated; and further study is still needed to unveil new features.

Since transmissibility can assess TMS and natural frequencies, then, the extended parameters based on modal parameters can later similarly be applied in transmissibility-based OMA.

2.4 Transmissibility application for outlier identification

Damage identification includes several stages: detection, locating, quantification, and remaining life assessment. All damage identifications follow the same procedure, (1) operational evaluation; (2) data acquisition, fusion, and cleansing; (3) feature extraction and information condensation; and (4) statistical mode development for feature discrimination [20]. The most essential step is feature extraction. Generally, feature means the property associated with the structural

Modal analysis	EMA	Transmissibility-based OMA
Kernel	FRF	Transmissibility
Coherence	FRF coherence	TC [17]
Modal parameters	Mode shape	TMS
	Frequency extraction techniques like SSI	Frequency extraction techniques like TC based [14]

Table 1.
Comparison between EMA and transmissibility-based OMA.

internal change. For instance, the cross section reduction will result in stiffness reduction, which later changes the structural dynamic responses. Then, features can be constructed from structural dynamic responses to assess the stiffness reduction (kind of damage).

Certainly, damage has more kinds, like spalling in concrete structures, corrosion induced defects, and so on. These kinds of defects at initial stage may not cause a clear change in stiffness reduction; thus, special techniques like acoustic emission should be adopted in further investigation.

For the damage illustrated in this study-stiffness reduction related damage, vibration-based techniques are taken into consideration. To construct damage indicator, the change of feature is the commonest, and one may use MAC for achieving a comparable indicator without needing normalization, which can be denoted as

$$DI = 1 - MAC = 1 - \frac{\left((TMS^u)^T \times (TMS^d)\right)^2}{\left((TMS^u)^T \times (TMS^u)\right) \times \left((TMS^d)^T \times (TMS^d)\right)} \quad (7)$$

where $(TMS)^u$ and $(TMS)^d$ denote the value under undamaged and damaged states, respectively.

Of course, herein, more indicators can be constructed, since TMS and natural frequencies are assessed by transmissibility in OMA, curvature, higher order derivative, and so on, and all these modal parameters based indicators can further be applied in damage detection [23].

3. Case study

In order to illustrate the feasibility of the proposed methodology, a pined-pined beam is numerically analyzed. Young's modulus is 185.2 GPa, dimension is $0.005 \times 0.006 \times 1.000$ m, density is 7800 Kg/m^3, and a vertical impulse is excited in the node 7 with 10 elements discretized on average in the whole beam. Dynamic responses are considered in the further OMA. The schematic diagram in **Figure 2** shows the beam. Different damage levels are simulated with reducing the stiffness in element 3, and for damage level D1, D2, D3, and D4, the stiffness reduced from 5, 10, 15, to 20% accordingly.

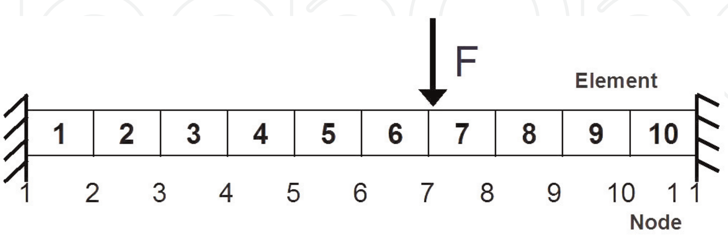

Figure 2.
Schematic diagram of the pined-pined beam.

4. Results and discussion

Results for the aforementioned methodology is computed and discussed in this section. **Figure 3** illustrates the mode shapes for first four modes, while **Figure 4** demonstrates the TMSs for first four modes, where one can find that both mode shapes and TMSs share the similar shapes, and their well agreement implies the potential use of TMS in damage identification.

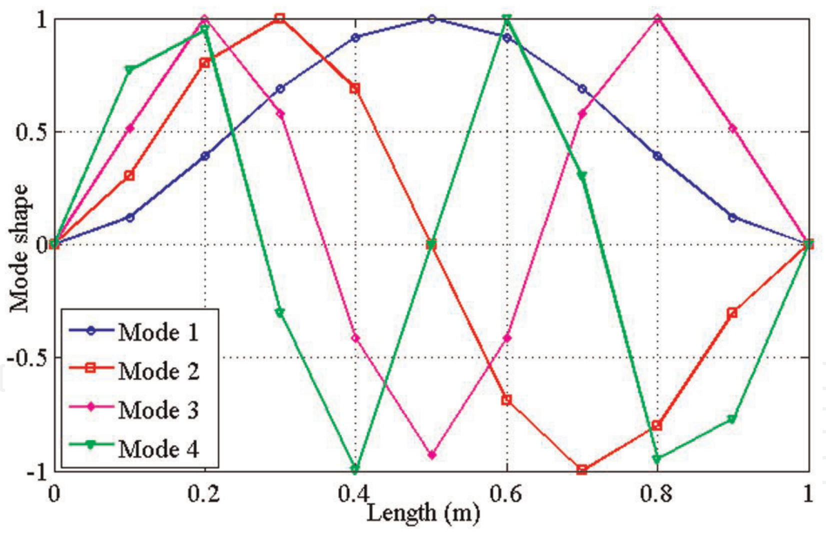

Figure 3.
Mode shapes of the beam for first four modes.

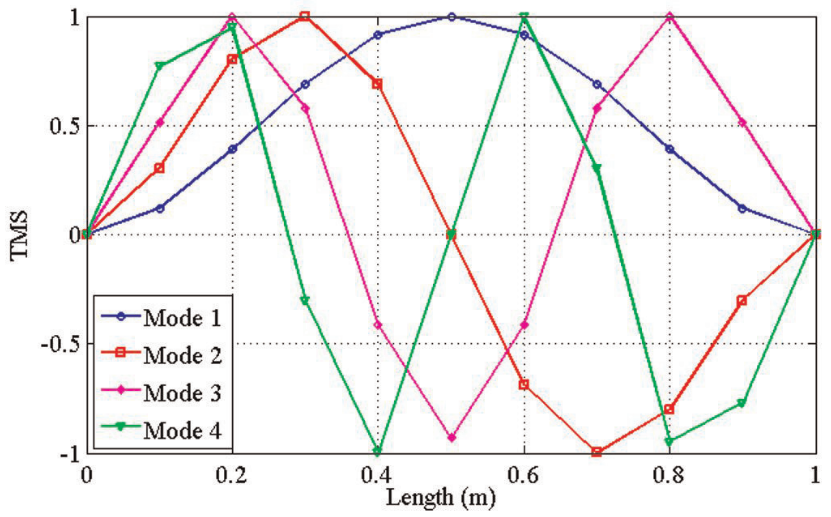

Figure 4.
TMSs of the beam for first four modes.

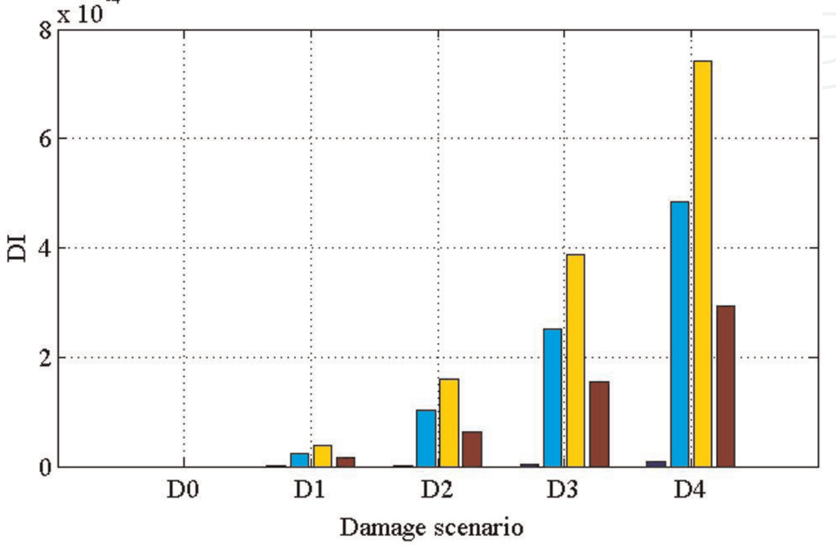

Figure 5.
DI for first four modes.

Figure 5 gives the structural detection results from the constructed damage indicator DI. From this figure, it can be found that all damage levels are detected. It should also be noted that the change of DI for all the four modes are not very much, this suggests that TMSs vary small before and after the occurrence of damage, and further enhancement should be conducted in order to achieve a better damage detection performance.

5. Concluding remarks

This study tries to discuss some insights for bridge condition monitoring, also extends the mode shape into transmissibility-based OMA, and by using transmissibility, TMS is assessed by analog of mode shape in EMA, which paves the way for further investigation of extending the mode shape-based indicators to TMS-based analysis [21, 22]. MAC is used to construct a damage indicator with being verified by a pined-pined beam. The damage detection performance implies further necessary investigation for obtaining a better and deeper understanding.

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References

[1] Cao H, Qian X, Zhou Y, Chen Z, Zhu H. Feasible range for midtower lateral stiffness in three-tower suspension bridges. Journal of Bridge Engineering. 2018;**23**(3):06017009

[2] Qin S, Zhou Y, Kang J. Footbridge serviceability analysis: From system identification to tuned mass damper implementation. KSCE Journal of Civil Engineering. 2019;**23**(2):754-762

[3] Storoy H, Sether J, Johannessen K. Fiber optical condition monitoring during a full scale destructive bridge test. Journal of Intelligent Material Systems and Structures. 1997;**8**:633-643

[4] Farhey DN. Bridge instrumentation and monitoring for structural diagnostics. Structural Health Monitoring. 2005;**4**(4):0301-0318

[5] Kim J-T, Park J-H, Lee B-J. Vibration-based damage monitoring in model plate-girder bridges under uncertain temperature conditions. Engineering Structures. 2007;**29**:1354-1365

[6] Kalicka M. Acoustic emission as a monitoring method in prestressed concrete bridges health condition evaluation. Journal of Acoustic Emission. 2009;**27**:18-26

[7] Chen Y, Feng MQ, Tan C-A. Bridge structural condition assessment based on vibration and traffic monitoring. Journal of Engineering Mechanics. 2009;**135**(8):747-758

[8] Xu Y-L. Making good use of structural health monitoring systems of long-span cable-supported bridges. Journal of Civil Structural Health Monitoring. 2018;**8**:477-497

[9] Xi R, Jiang W, Meng X, Chen H, Chen Q. Bridge monitoring using BDS-RTK and GPS-RTK techniques. Measurement. 2018;**120**:128-139

[10] Kim S-W, Jeon B-G, Cheung J-H, Kim S-D, Park J-B. Stay cable tension estimation using a vision-based monitoring system under various weather conditions. Journal of Civil Structural Health Monitoring. 2017;**7**:343-357

[11] Maizuar M, Zhang L, Miramini S, Mendis P, Thompson RG. Detecting structural damage to bridge girders using radar interferometry and computational modeling. Journal of Structural Control and Health Monitoring. 2017;**10**(24):1-6

[12] Vaghefi K, Oats RC, harris DK, Ahlborn TM, Broooks CN, Endsley KA, et al. Evaluation of commercially available remote sensors for highway bridge condition assessment. Journal of Bridge Engineering. 2012;**17**(6):886-895

[13] Zhou Y, Maia NMM, Sampaio RPC, Wahab MA. Structural damage detection using transmissibility together hierarchical clustering analysis and similarity measure. Structural Health Monitoring-An International Journal. 2017;**16**(6):711-731

[14] Zhou Y. Structural Health Monitoring by Using Transmissibility [PhD thesis]. Spain: Technical University of Madrid; 2015

[15] Zhou Y, Wahab MA. Cosine based and extended transmissibility damage indicators for structural damage detection. Engineering Structures. 2017;**141**:175-183

[16] Zhou Y, Figueiredo E, Maia NMM, Sampaio R, Perera R. Damage detection in structures using a transmissibility-based Mahalanobis distance. Structural Control and Health Monitoring. 2015;**22**:1209-1222

[17] Zhou Y, Figueiredo E, Maia NMM, Perera R. Damage detection and

quantification using transmissibility coherence analysis. Shock and Vibration. 2015. Article ID 290714, 16 pages

[18] Zhou Y, Cao H, Liu Q, Wahab MA. Output-based structural damage detection by using correlation analysis together with transmissibility. Materials. 2017;**10**:866

[19] Zhou Y, Qian X, Birnie A, Zhao X. A reference free ultrasonic phased array to identify surface cracks in welded steel pipes based on transmissibility. International Journal of Pressure Vessels and Piping. 2018;**168**:66-78

[20] Sohn H, Farrar CR, Hemez FM, Shunk DD, Stinemates DW, Nadler BR, Czarnecki JJ. (2004). A Review of Structural Health Monitoring Literature: 1996–2001, los Alamos National Laboratory Report, LA-13976-MS, 2004

[21] Kerrouche A, Boyle WJO, Gebremichael Y, Sun T, Grattan KTV, Täljsten B, et al. Field tests of fibre bragg grating sensors incorporated into CFRP for railway bridge strengthening condition monitoring. Sensors and Actuators A. 2008;**148**:68-74

[22] Dissanayake PBR, Karunananda PAK. Reliability index for structural health monitoring of aging bridges. Structural Health Monitoring. 2008;**7**(2):0175-0179

[23] Zhou Y, Maia NMM, Wahab MA. Damage detection using transmissibility compressed by principal component analysis enhanced with distance measure. Journal of Vibration and Control. 2018;**24**(10):2001-2019