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RESEARCH ARTICLE

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Modal plot—System identification and fault detection

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Summary

The damage identification is one of the primary concerns in structural health monitoring. Among the available studies, various authors have proposed several approaches for damage detection as well as certain parameters to be monitored (damage indicators) based on the "Output only Modal Analysis." In this study, "Level 0" fault detection is investigated by using modal properties. The utilization of modal properties has been established since the 1970s-1980s in a number of configurations. Within the context of this study, novel concepts and parameters such as the "*Modal Plot*," the "*Count Plot*," and the "*Modal Zones*" are introduced for system identification and damage detection. Modal parameters are identified via the modal and count plots, and the damage presence is detected from the modal zones in the modal plot. The modal plot is a method that contributes to the stabilization diagrams, and the count plot is an alternative approach for the power spectral density diagrams. Moreover, the modal zone is observed as a damage sensitive parameter in the experimental study.

KEYWORDS

count plot, damage detection, modal parameter identification, modal plot, modal zone

1 | INTRODUCTION

Detection of the structural damage from the measured structural response is related to many steps associated with many disciplines. The system identification is one of the most important steps among them and is at the center of the analysis. The parameters related to the health of the structure can be determined by means of system identification techniques, which require the measured structural responses caused by the environmental disturbances (i.e., input forces). In practice, however, there are certain challenges such as the limited amount of response measurement stations and difficulties in measuring the external forces. Vibration-based system identification studies often rely on the white noise assumption where the operational external forces are modeled as a noise exciting "uniformly" all the frequency components.[1-3] The white noise assumption facilitates identifying the parameters related to the dynamic behavior of the structure under daily (operational) loads. In the literature, such approaches, which are based only on the system response, is called Operational Modal Analysis.[4]

In general, the environmental factors affecting the structural response constantly change during the operation. Therefore, the "Structural Health Monitoring" (SHM) systems are desired to be able to eliminate the effects of environmental factors on the components (software and hardware) of the SHM systems. The changes in the ambient temperature, air pressure, and humidity can alter the material properties, and hence, the system properties are likely to change. In most cases, the source of the change in the structural response related to the environmental effects is not directly associated with the structural health. Instead, it is tended to be attributed to the structural damage.

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The aim of this study is (a) to introduce a new system identification method for estimating modal parameters and (b) to propose a novel damage indicator for the damage existence problem. In the system identification part of this study, it is shown that the modal parameters can be estimated accurately by using the "*Count Plots*." The count plot—defined in the time domain—is an alternative for the power spectral density (PSD) estimates in the frequency domain. In both methods, the modal parameters are determined from the peaks.

The accumulation of frequency and mode shape estimates of a system is described as the "*Modal Plot*" in this study. In the experimental study, it is observed that the "*Modal Zone*" in the Modal Plot is sensitive to the presence of damage in the system. The damage causes a discontinuity in the modal zone, which is a sign of the damage. Thus, the presence of damage in the structure can be determined graphically without baseline information. To the best of our knowledge, there has been no such technique in SHM literature that is used to detect the existence of damage by a certain type of variation in a graph. It is difficult to detect the presence of damage by evaluating the natural frequency changes because the environmental factors may cause similar effects on the natural frequencies. Therefore, the proposed method for damage detection offers a novel approach to the literature.

1.1 | Damage diagnosis and its levels

Damage is a word that encompasses many scales and severities. A unique definition generally requires the identification of certain thresholds, which invariably depend on the specific application. It is generally agreed, however, that the damage identification methods can be systematically categorized in the following order (see, e.g., other studies[5,6]):

Level 0: (Fault Detection) Determining whether the damage exists in the structure.
Level 1: (Fault Identification) Detection of the geometric location of the damage.
Level 2: (Magnitude Estimation) Quantification of the severity of the damage.
Level 3: Prediction of the remaining service life of the structure.

In addition to the aforementioned levels, some researchers[7] put emphasis on the importance of discrimination of damage type. Some of the examples of the damage entities are cracks, corrosion, material deformation, and loose connections.

In the literature, the studies related to the effect of the damage on modal variables have revealed that for minor damages, the change in the natural frequencies is linear with the severity of the damage and is nonlinear with the location of the damage.[8,9] Therefore, for small damage extents, if the location of damage (Level 1) is identified properly, then the determination of the damage extent (Level 2) becomes easier.[9] Moreover, it is a fact that the fault identification (Level 1) problem covers fault detection (Level 0) problem. Therefore, the Level 1 problem is the main focus in most of the studies.[10] However, conducting a proper Level 0 fault detection is also vital for the next levels. One of the goals of this study is to show that Level 0 damage detection can be accomplished by using the first modal information.[9,11]

1.2 | Extraction of damage sensitive features

To perform a robust evaluation of the structure and determining reliable damage indicators, which are strongly associated with the system's *capacity* (damage sensitive features), are crucial in the condition assessment of a given structure. Furthermore, the external effects (input forces) in the surrounding environment must be elaborately investigated and comprehended. Upon identification of the capacity, it is required to evaluate the response (*demand*) under the operating condition of the system.

Vibration-based methods aim to use such a damage-sensitive feature that is simple, small in size, easily estimated, sensitive to changes in the capacity, and nonsensitive to changes in demand. Some of the features used in the literature, simple to complex, are modal parameters (frequencies, mode shapes, and less frequently damping), signal parameters (e.g., cepstrum and electromyography signals), and model parameters (e.g., autoregressive model parameters). In this study, the modal parameters are used as damage-sensitive variables.

2 | SYSTEM IDENTIFICATION

In the linear systems, the modal analysis approach can be considered valid when the structure is under environmental vibrations. In discrete systems, the number of the natural frequencies and the mode shapes, in theory, is equal to the degree of freedom of the structure. It can be considered that the number of sensors used in the measurement does not limit the number of natural frequencies determined based on the vibration data. However, because the higher modes often do not contribute significantly to global responses, it may not be possible to determine these high modes from measurements. The determination of the mode shape would be limited by the number of sensors used.

In order to determine the dynamic variables such as natural frequencies, mode shapes, and damping ratios, many methods have been proposed in the literature. It is possible to classify these approaches under two main categories: the frequency domain and the time domain approaches. It is stated that the frequency domain methods are suitable for the systems with a damping ratio higher than 0.3%, and the time domain methods are appropriate for systems with a damping ratio of less than 5%.[12] The civil engineering structures are generally within these limits.

The Fourier transform and frequency response functions (FRF) are frequently used in the frequency domain methods. The system is defined by FRF, which is a transfer function type and contains the dynamic characteristics of the system. The FRF can be calculated as the ratio of the Fourier transform of the response to the Fourier transform of the input force. When the amplitude of the FRF, which is a complex function, is plotted, the frequency values corresponding to the peaks are considered to be the natural frequencies of the structure. The mode shapes can be determined by evaluating the ratio of the amplitudes of the peaks for each sensor, together with the angle of the FRF.[13] If it is assumed that the PSD of the input force under operating loads is approximately equal in all frequency values (white noise assumption), the natural frequencies and the mode shapes can be calculated directly via the Fourier transform of the response. If the input forces do not comply with the white noise assumption, the history of the input forces must be measured and should be taken into account. The two most important problems of frequency domain methods are[14] the generation of new frequencies (spectral leakage) that are not related to the natural frequencies of the structure and a noisy FRF from the noise-free data while converting from time domain to frequency domain under operating loads.

Time domain methods are also frequently used in the identification of the system. The time-domain methods define a model that uses only the response or both the response and the input force histories when calculating the modal variables. It is important to determine the model order so that the model is consistent with the examined data.[15] Theoretically, it is assumed that only true modes are calculated with a correct ordered model; in practice, besides the physical modes of the structure, the computational modes (that reduce the undesirable effects such as noise and leakage in the data[16,17] and are thought to be irrelevant to the system characteristics) are also estimated. Moreover, it is aimed to accurately estimate a certain number of structural modes depending on the type of the problem because it is not possible to detect all modes in the continuous systems. Furthermore, as the model order increases, the number of computational modes also increases. For these reasons, the choice of the model order and the discrimination of physical and computational modes are important issues in the time domain methods. There are many tools that address to solve the aforementioned issues, and one of them is the stabilization diagrams.

2.1 | Stabilization diagrams

In some of the time domain methods, the model order must be determined at one stage. Precise determination of the model order is a difficult step due to the deviations in assumptions of the model and the presence of the noise in the data. In addition to the Akaike[18] and Bayes[15] Information Criterion, an approach called stabilization diagram is frequently used to determine the model order with relatively small errors. The stabilization diagram represents the stability of the selected modal variables according to the increasing model order.[19] The plotting and representation of the stabilization diagrams can be summarized in three steps:

1) A sufficiently high-degree model is selected, and the values of the modal variables are calculated according to the degree of the model.
2) The model order is incremented, and the modal variables are recalculated. Compared with the values calculated in the previous model, it is observed which modes continue to be seen despite the model order change. In determining this continuity, the natural frequencies, the damping ratios, and the Modal Assurance Criteria,[20] which depend on mode shape, are also compared.

3) Once a sufficient number of models are assessed, the modes that appear in most of the models are evaluated as stable and are considered to be structural modes.

Although the stabilization diagram is a common utility, it contains many iterations and often requires user intervention. In the next section, the modal plot approach, which is a new method designed as an alternative to the stabilization diagram, is explained below.

2.2 | Modal plot

Modal plot is a plot that shows the interaction of all estimated frequencies and corresponding mode shapes of high-order time domain model. Estimation of the natural frequencies and the mode shapes accurately at the same time (in the same graph) is one of the main concerns of the modal plot. When the term modal is used, there would be an expectation to relate it with the three modal parameters, which are the modal frequencies, the mode shapes, and the modal damping ratios. The plot consists of the first two, and it will be depicted (in Section 3.1) that how the modal plot is related to the modal damping. Moreover, the definition of the modal zones of the computational estimates is also one of the issues to be dealt with in Section 3.1 for the discrete systems and in Section 3.2 for the continuous systems.

In all analyses, the "Output Only Observer Kalman Filter Identification" (O^3KID) followed by the "Eigen System Realization Algorithm" (ERA) is used.[21,22] The input forces acting on the system are assumed to be white noise.

The number of singular values is used as much as possible in the second step, ERA, in order to estimate as many modal parameters as possible, and a further elimination step as in the stabilization diagram (Section 2.1) is not required.

In modal parameter estimation process, the mode shapes of the reference degree of freedom is taken as one "1," and the modal plots are converted to count plots in the identification of real modes.

2.3 | Count plots

An important purpose of the count plot is the simultaneous determination of the true natural frequencies and mode shapes of a system. The prediction, which the approach is based on is that the modal variables calculated by the system identification methods contain errors, even in small amounts. However, when different data sets are used, the scattering in the "actual" modes will be smaller compared with the "computational" modes. For the same system, when different models are set up using the data collected within the time period that the system properties are assumed not to change, the same mode variables cannot be estimated exactly. However, it can be said that the values within certain limits represent the same mode. Based on this clustering approach, the number of the modal variable estimates lying within certain limits are counted and are plotted based on the frequency values to obtain the count plot. The frequencies that correspond to the peaks in the count plots correspond to the natural frequencies of the structural modes. Because both the frequencies and the mode shapes are used in the clustering, the average of the frequency and mode-shape prediction sets corresponding to the peaks can be calculated automatically. Thus, the "real" natural frequencies and mode shapes of the system (the modal point) are estimated. Because the modal variables are calculated according to the peaks, the count plot, which directly processes in the time domain, is quite similar to the PSD calculated via the Fourier transforms of the response signals.

3 | CASE STUDIES

The aim of each case study is to understand one or more properties of the modal plot. In the first case study, modal parameters of the discrete system are identified using the modal plots and the count plots. The first case study also elaborates modal plots and its conversion to count plots as well as parameters affecting the modal plot. The second case study is an experimental study, which aims to identify the damage in a continuous system using the modal plots.

3.1 | Case study I: System identification with modal plot

This part is related to the discrete system identification, and the aim of this case study is to demonstrate how to estimate modal parameters using the modal plot.

The properties of the analyzed structural system are given in the following list and in Table 1:

(1) There is no noise in the response.
(2) There is no damping in the system.
(3) Input is known, and it is pure white noise.
(4) Input force is applied at the free end.
(5) Modal parameters are time-invariant.
(6) The numerical model is known, so the error in each estimate can be calculated.

Ambient vibration is applied at the free end. The ambient acceleration used in the analysis and the response retrieved in the first DOF are shown in Figures 1 and 2, respectively.

The power spectral density function of the response is shown in Figure 3. Peaks are clear, well separated, and correspond to the frequency calculated from the eigenvalues of the system.

The response is processed as follows in the modal plot:

TABLE 1 Numerical analysis specifications

# of DOFs	**15**
End conditions	Fixed-free
Spring stiffness	4.54E8 N/m
1st–14th DOF mass	4530 kg
15th DOF mass	2265 kg
Damping	No
Input DOF	15th DOF
Input type	Ambient vibration

Note. DOF: degree of freedom.

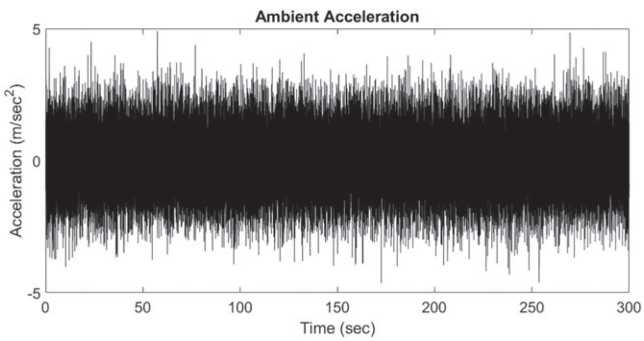

FIGURE 1 Ambient acceleration applied to the system

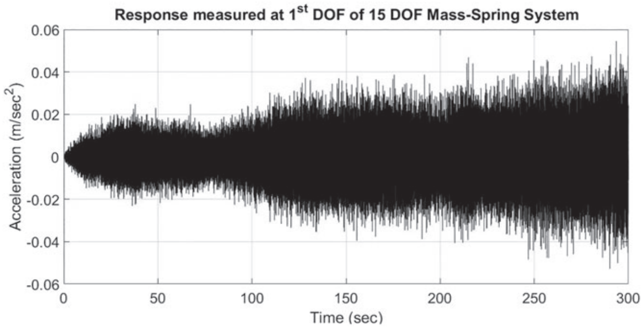

FIGURE 2 Ambient response measured at the first degree of freedom

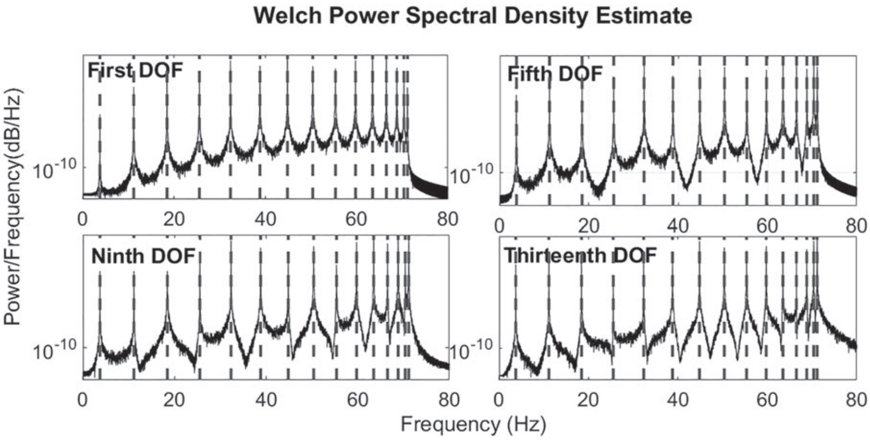

FIGURE 3 Welch power spectral density estimates for the 1st, 5th, 9th, and 13th degrees of freedom

In each analysis, four measurement locations are considered. The last DOF is taken as a reference DOF, and the remaining 14 DOFs are analyzed in five steps such that in the first step, the 1st, 2nd, 3rd, and the 15th DOFs are analyzed, and in the last step the 1st, 13th, 14th, and the 15th DOFs are analyzed. Therefore, the first DOF is analyzed twice.

In each step, the response is divided into sections. Each response section has 80% overlap with the next section.

(O^3KID) A relatively high model order is chosen (in this example, model order is 300), and more than 5,000 Markov Parameters are calculated.

(ERA) The Markov Parameters are used in a square Hankel Matrix, which is greater than 4,000 by 4,000. The sizes of the matrices A and C are not reduced, and they are converted to modal parameters.

When all computation process is done, the modal parameters are presented as the modal plot as in Figure 4.

The modal plot for the first DOF and the other DOFs have around 20,000 and 10,000 estimates, respectively, between 0 and 40 Hz.

In Figure 4, the natural frequencies and the mode shapes of the system are shown as circles. They are referred to as modal points. All estimates, which are not close to modal points, are defined as the calculated modes. Using these two definitions, the modal zones (Figure 4) are defined as zones containing the modal points and curves of the surrounding computational modes. For the discrete systems other than modal points, computational modes are relevant to modal points, but using them is irrelevant.

The estimates of modal parameters are represented as points in Figure 4. For the identification purposes, the modal plots are converted to the count plots as follows (Section 2.2 and 2.3):

(1) (Optional) Order all estimates according to the frequency values (Time consideration).
(2) Define a tolerance limit for the mode shape and the natural frequency as in Figure 5.
(3) For an estimate, count estimated points other than itself within the tolerance limit.
(4) Repeat the third step for all estimated points.
(5) Plot counts versus frequencies for all estimates as in Figure 6. This plot is referred to as "Count Plots."

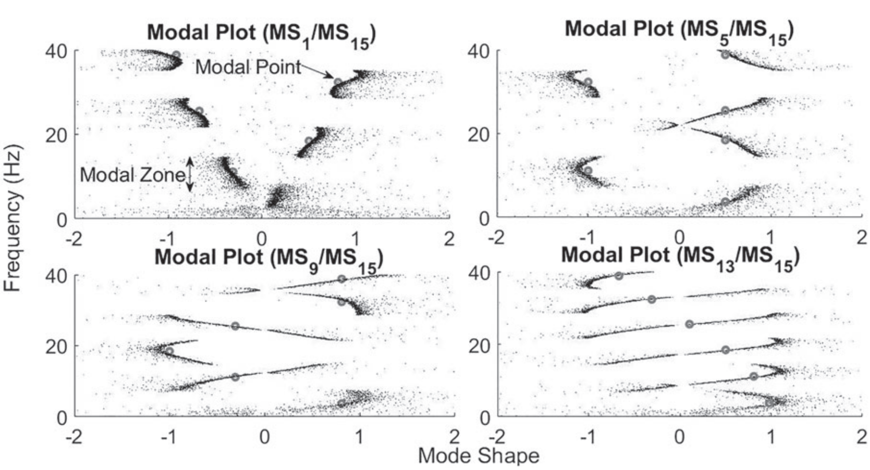

FIGURE 4 Modal plot for various degrees of freedom

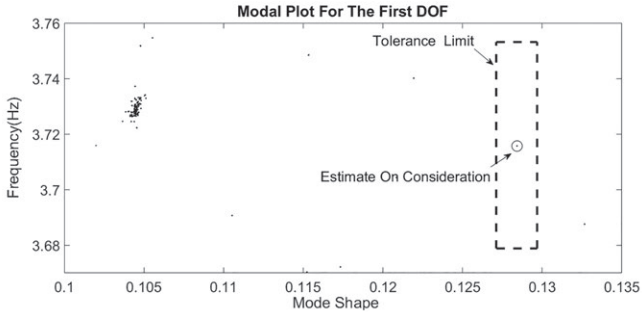

FIGURE 5 Modal plot tolerance limits

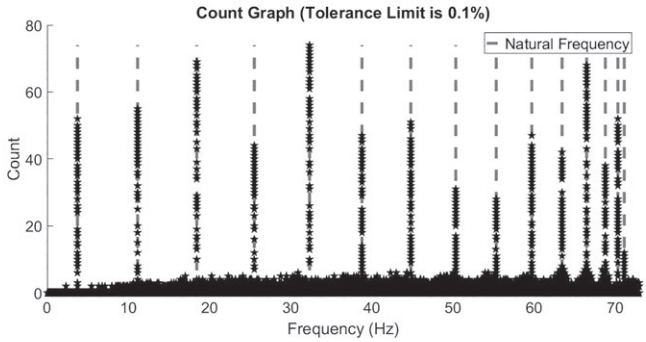

FIGURE 6 Count graph for 0.1% tolerance limit

The natural frequencies calculated from the known system and the count plot peaks are compatible with each other as can be seen in Figure 6. The mode shape values are calculated as the average value of the accumulation of points, which contains one of the peaks of the count plots (Figure 7).

Figure 8 shows the comparison between the eigenvector of the system with estimated mode shapes for the first four modes. A very close match is attained for each mode and each DOF. The results show that maximum errors in the mode shape in percentage are 0.055, 0.067, 0.082, and 0.147 for the first four modes, respectively. Therefore, the count plots and the modal plots give satisfactorily accurate results.

It should be noted that if the tolerance limit is chosen as 1% for each modal parameter, then counts of nonreal modes may also include assembly of real modal parameters as in Figure 9. Therefore, it is logical to define tolerance limit as a low percentage or as a number.

As a result, the modal plot is an efficient tool for modal parameter estimation under no damping and no noise case. However, as the noise and the damping ratio increase, the accumulation of points may not appear in the modal plots (Figure 10).

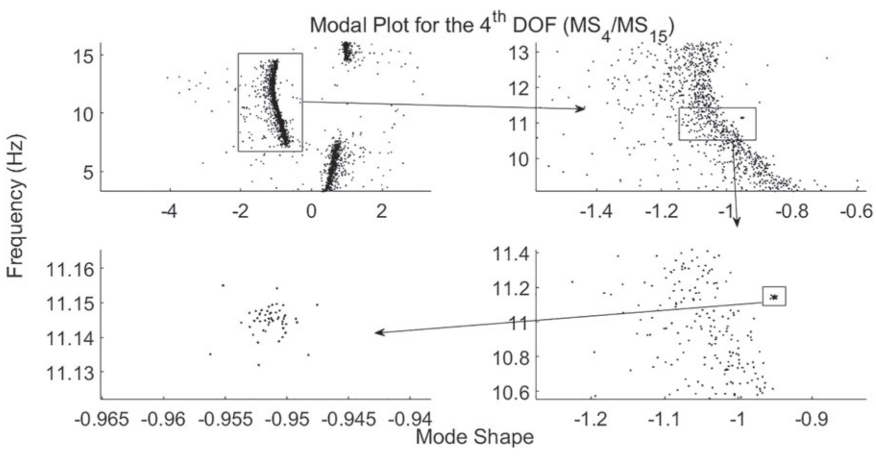

FIGURE 7 Accumulation of estimates in modal parameters for DOF: 4

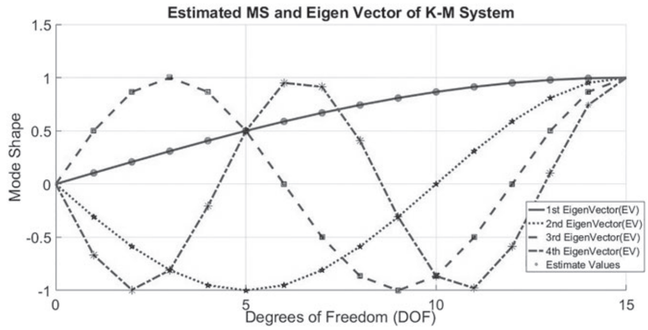

FIGURE 8 The first four mode shapes: lines: eigenvector; markers: estimated values using the count plot

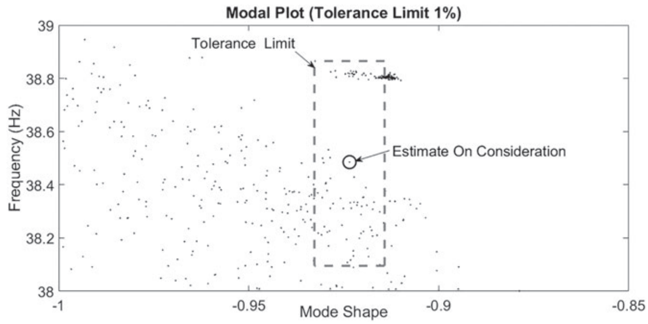

FIGURE 9 Modal plot: 1% tolerance limit

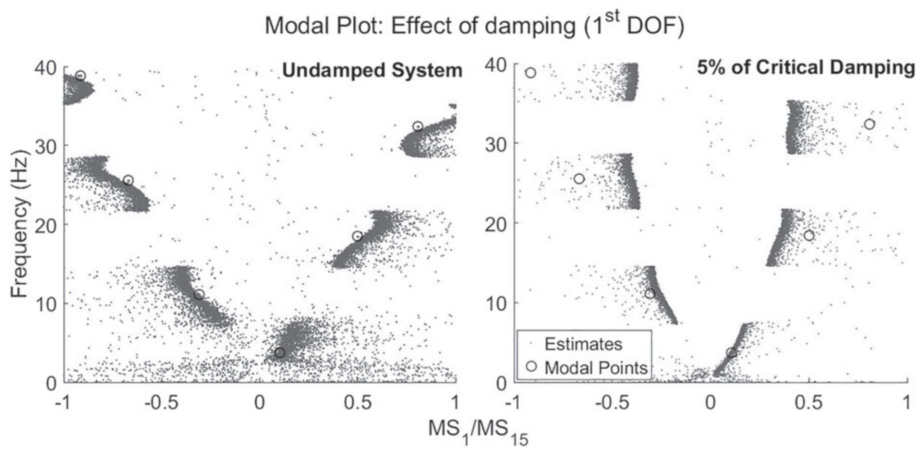

FIGURE 10 Change in modal plot for varying damping for the 1st degree of freedom

As an alternative to the count plots, the histogram plots can also be used for the frequency estimates. In Figure 11, the peaks appear at the natural frequency values in the histogram plot. The counts in the histogram are higher than that in the count plot at natural frequencies. However, the error in histogram plot is much higher than in the count plots.

3.2 | Case study II: Beam with hinges

In this experimental study, it is aspired to detect the damage in a steel beam. For this purpose, an intact steel beam with a hollow-rectangular cross-section is divided into nine equal (almost) pieces with a cut angle of 45^0 and reconnected with each other using two bolts and a nail. The properties of the cross-section dimensions are 40 × 40 mm, and the thickness varies from 1.6 to 2 mm. A hole in the size of the diameter of the nail is drilled into the sample at the center of the connection in the transverse direction. The nails are placed into these holes in order to prevent sliding. When

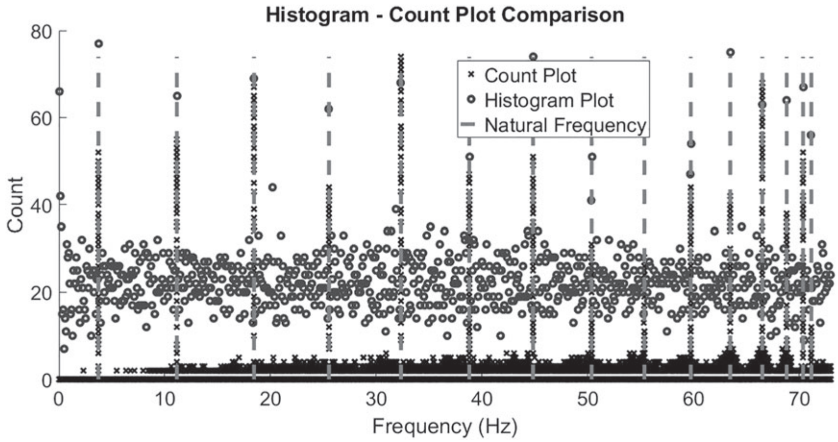

FIGURE 11 Histogram using frequency estimates and count plot comparison

bolts are loosened, sliding occurs in the connection zone. Because the nail stands still in the hole, a small angle reducing the interacting area eventually results in a decrease in the local damping and stiffness of the system (Figure 12).

In this study, only one damage case is considered, and the system is measured at seven different locations. The system properties change depending on the measurement location due to the mass of the accelerometer. The mass of the accelerometer is 345.88 g, and mass of each piece of the sample is around 280 g. When measurement location is changed, the mass distribution of the system also changes, which results in a variation in the system in every measurement. Therefore, the same damage type is tested for seven similar but different systems in this case study.

The damage is defined as loosening of two of the bolts at the 5th piece from the fixed end (Figure 13). The amount of loosening is defined such that one can loosen bolts up by hand easily.

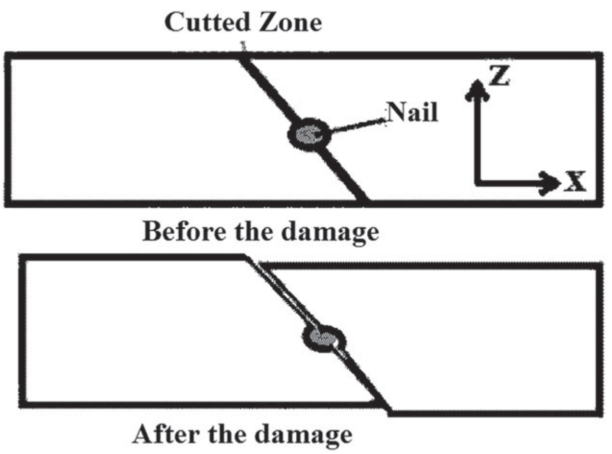

FIGURE 12 Damage representation

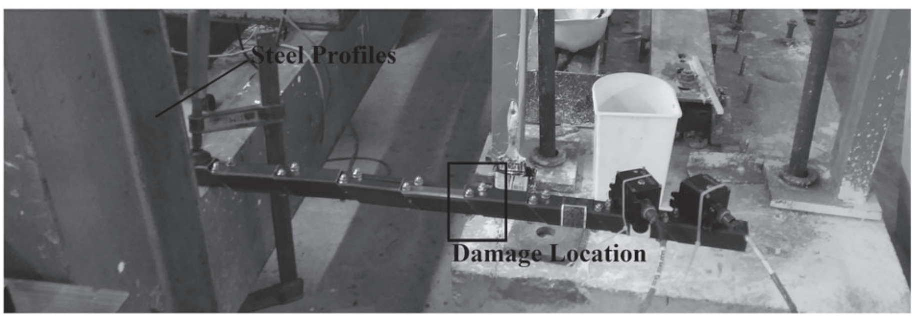

FIGURE 13 Experimental setup and black box showing damage position

The duration is 5 min for each measurement. The measurements are conducted by using two z direction accelerometers with a sampling rate of 200 Hz. One of the accelerometers is used as a reference measurement, and it is always located at the last piece from fixed hand side. The position of the other accelerometer is changed. The rotation of the sensors is prevented by the help of the bolts as seen in Figure 14.

The measurements are done in the following order as piece number from the fixed end:

Before damage: 7th, 6th, 5th, 4th, 3rd, 2nd, 1st (piece).
After damage: 1st, 2nd, 3rd, 4th, 5th, 6th, 7th (piece).

A periodic force is applied to the steel sections with fingertips starting before the onset of damage in the 2nd piece (from fixed end) measurement and applied most of the measurements in order to see the effect of the amplitude variation of the input force in the modal plot. No force is applied to the system directly. The l_1 and l_2 norms of the normalized response measurement at the reference measurement are given in Table 2. The normalization process contains only removing the mean of almost 7-s response to itself. The footsteps of the people passing by sometimes cause impulse type input excitations to the system. They are removed from the signal. Thus, some of the modal plots provide fewer estimates than the others.

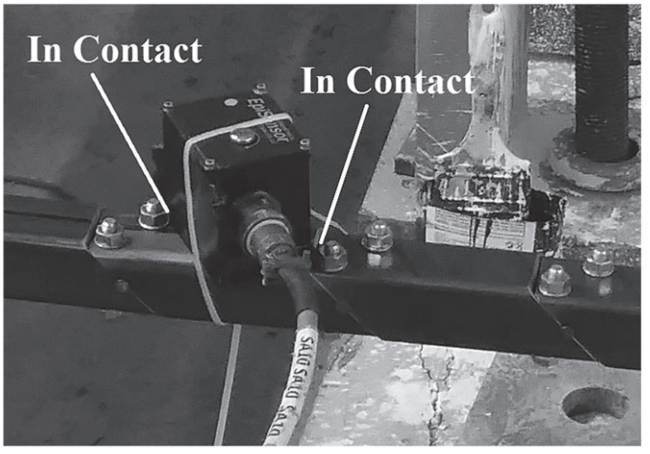

FIGURE 14 Accelerometer orientation

TABLE 2 Input information

Second sensor location	Damage type	l_1	l_2
1	Undamaged	16.812	0.341
1	Damaged	55.646	0.669
2	Undamaged	2.776	0.017
2	Damaged	2.523	0.014
3	Undamaged	2.317	0.013
3	Damaged	4.778	0.070
4	Undamaged	2.597	0.017
4	Damaged	5.601	0.066
5	Undamaged	2.950	0.015
5	Damaged	3.599	0.022
6	Undamaged	3.000	0.021
6	Damaged	5.123	0.035
7	Undamaged	2.279	0.011
7	Damaged	2.737	0.015

The Modal plots of the systems with the same mass distribution for the undamaged and damaged cases are given in two subplots as in Figure 15, and distinct peaks can be observed in the count plot (Figure 16).

From Figures 17–22, it can be seen that the damage changed the first modal zone from 10–11 Hz down to 9–10 Hz. Moreover, at every postdamage measurement, there is a separation in the modal zone between 9 and 10 Hz, which is

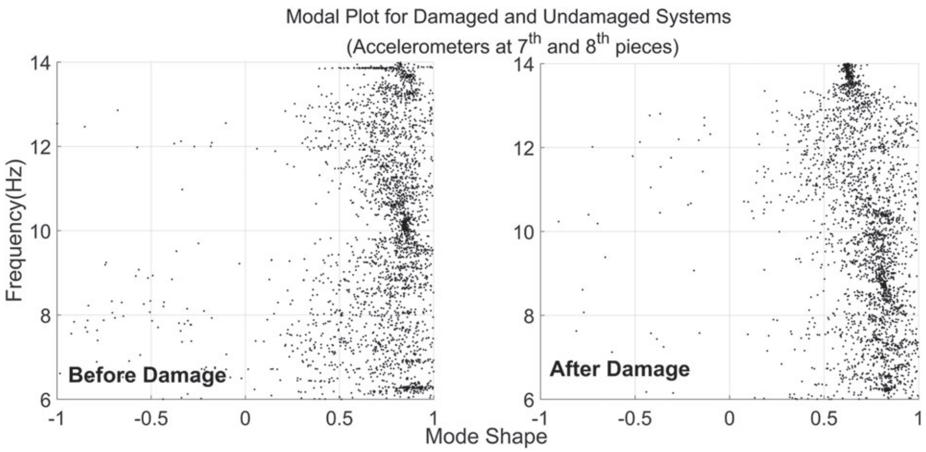

FIGURE 15 Modal plot for damaged and undamaged systems (accelerometers at 7th and 8th piece)

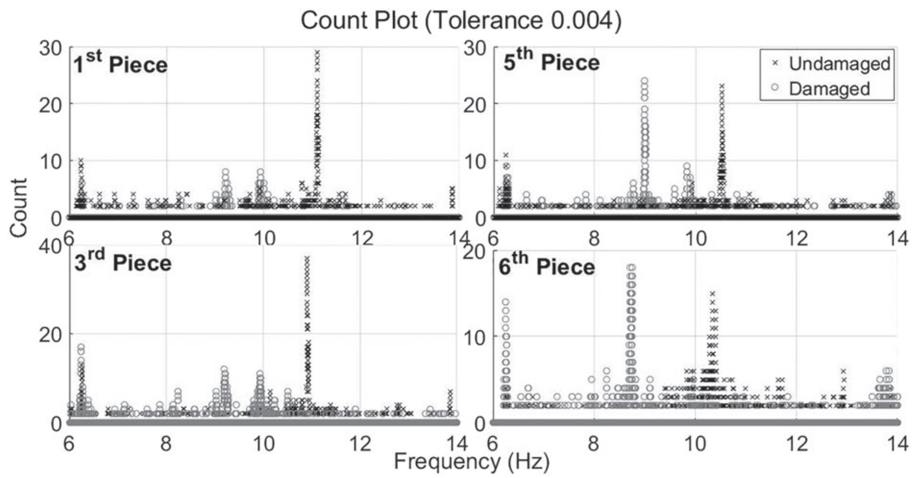

FIGURE 16 Count plot (tolerance limit 0.004)

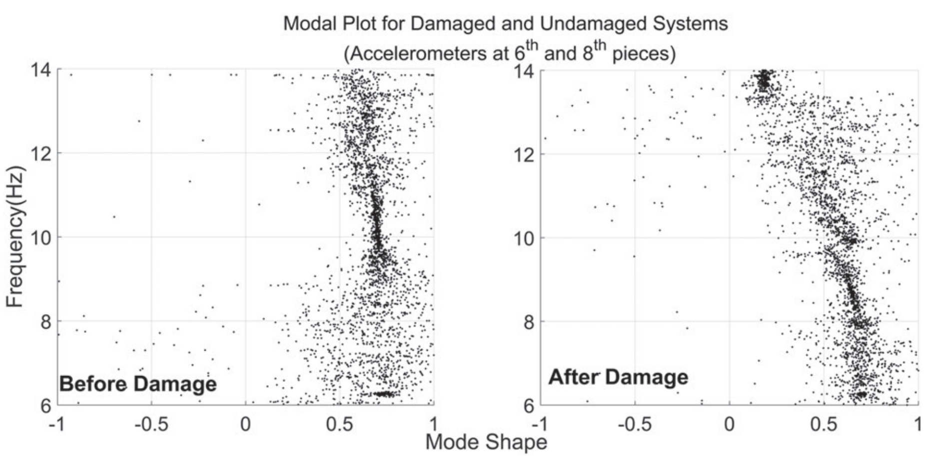

FIGURE 17 Modal plot for damaged and undamaged systems (accelerometers at 6th and 8th piece)

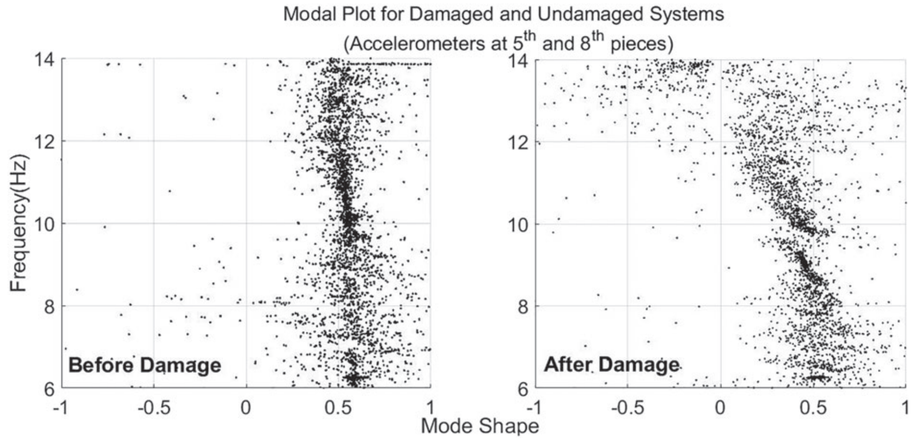

FIGURE 18 Modal plot for damaged and undamaged systems (accelerometers at 5th and 8th piece)

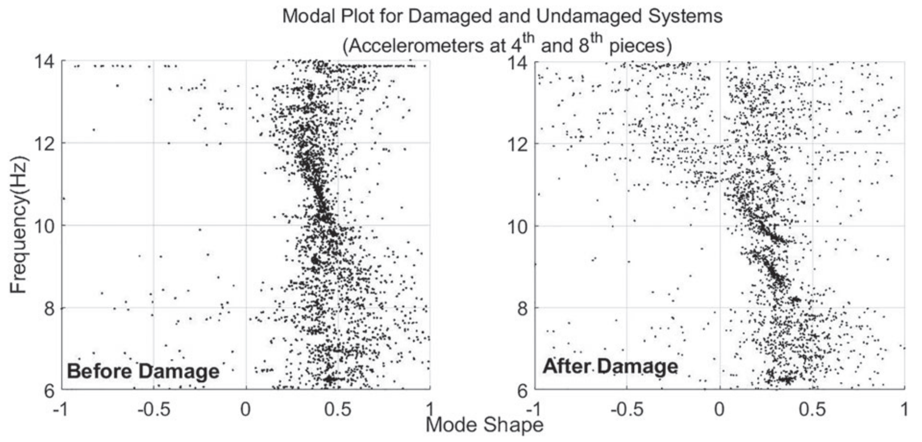

FIGURE 19 Modal plot for damaged and undamaged systems (accelerometers at 4th and 8th piece)

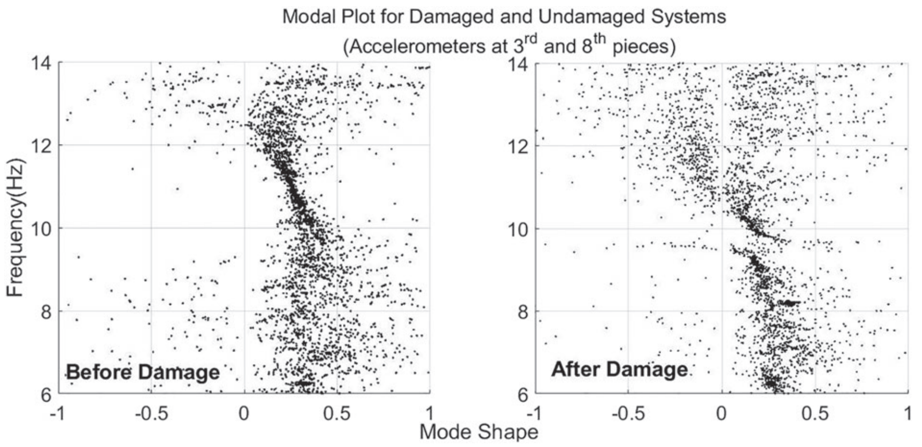

FIGURE 20 Modal plot for damaged and undamaged systems (accelerometers at 3rd and 8th piece)

not encountered in the predamage counterparts between 10 and 11 Hz. Systems have different mass distributions but have the same end conditions, and they are damaged at the same location with the same damage extent. Also, ambient vibration magnitudes are different as can be seen in Table 2. In addition, the same behavior is observed in the six postdamage measurements, and there is no evidence of such behavior in the measurements before the damage. Therefore, computed modes in the modal zone other than the modal points are also meaningful and can be used as damage-sensitive parameter for Level 0 damage detection problem.

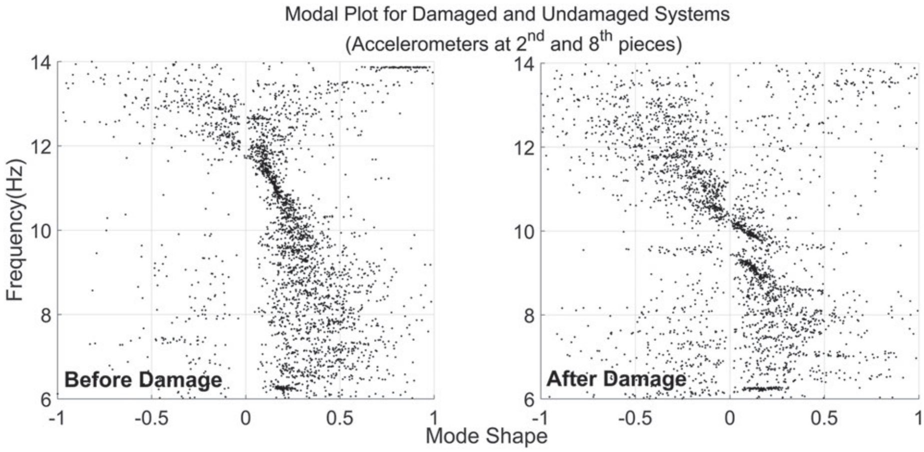

FIGURE 21 Modal plot for damaged and undamaged systems (accelerometers at 2nd and 8th piece)

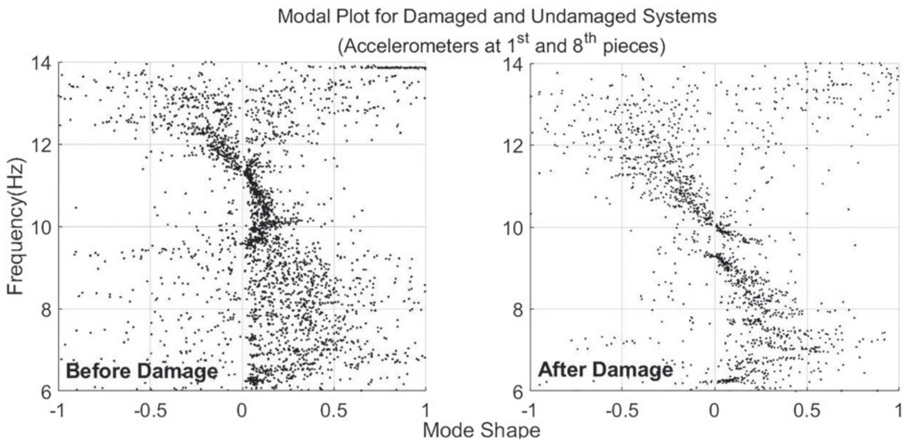

FIGURE 22 Modal plot for damaged and undamaged systems (accelerometers at 1st and 8th piece)

To sum up, the ambient vibration amplitudes are different for predamage and postdamage measurements. The same type of behavior in the same frequency range is detected for different but similar systems. For continuous systems, the modal zones are independent of the change in demand (due to a change in input forces) and dependent on the change in the capacity of the system.

Therefore, modal zones can be proposed as a useful damage sensitive feature for Level 0 damage detection problem.

4 | CONCLUSION

The modal plots are improvements on the stabilization diagrams. In order to eliminate the model order issue in stabilization diagrams, higher model orders are selected for the time series model. It is aimed in the modal plot to represent the mode shape and the natural frequency estimates at the same time. The Modal Plots are converted to the count plots for identification purposes. The count plot is an alternative for the PSD diagrams and used in the modal parameter estimation. Case studies for a discrete (numerical study) system and for a continuous system (experimental study) are performed. For the first case study, it is aimed to attain modal parameters (modal points) with small errors using the modal plot and the count plot. The results show that the modal points can be estimated with less than 0.1% error and even less for the first mode under an ideal response. Therefore, for light damping and low noise case, modal parameters can be estimated using the modal plot and the count plot. It is important to apply the input force in the same location. Also, parameters affecting the modal plot is explained briefly in the first case study.

In the second case study, which is experimental, it is shown that Level 0 damage detection can be done with the help of modal properties. The use of modal properties has been established since the 1970s and 1980s in a number of configurations. However, the introduction of the modal zones (which is a damage sensitive parameter) is a novel concept. The structural damage causes a discontinuity in the modal zones, which is a sign of the damage in the system. In this study, only first modal information is used, and the validity of using the first modal information is referred to in the Section 1.1.

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REFERENCES

1. Peeters B. System identification and damage detection in civil engineering [PhD thesis]. Leuven, Belgium: Katholieke universiteit; 2000.
2. Ren WX, Zong ZH. Output-only modal parameter identification of civil engineering structures. *Struct Eng Mech*. 2004;17(3–4):429-444.
3. Yang JN. Application of optimal control theory to civil engineering structures. *J Eng Mech*. 1975;101(6):819-838.
4. Peeters B, De Roeck G. Stochastic system identification for operational modal analysis: a review. *J Dyn Syst Meas Control*. 2001;123(4):659-667.
5. Fassois SD, Sakellariou JS. In: Boller C, Fujino F, Chang Y, eds. *Statistical Time Series Methods for SHM*. Chichester, UK: John Wiley and Sons Ltd; 2009:443–472. https://doi.org/10.1002/9780470061626.shm044
6. Rytter A. Vibrational based inspection of civil engineering structures [PhD thesis]. Denmark: Aalborg University; 1993.
7. Ayres JW, Lalande F, Chaudhry Z, Rogers CA. Qualitative impedance-based health monitoring of civil infrastructures. *Smart Mater Struct*. 1998;7(5):599-605.
8. Gladwell GML. *Inverse problems in vibration*. Dordrecht: Kluwer Academic Publishers; c; 2004.
9. Yuen MMF. A numerical study of the eigenparameters of a damaged cantilever. *J Sound Vib*. 1985;103(3):301-310.
10. Doebling, SW, Farrar CR, Prime MB, Shevitz DW. Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review (No. LA-13070-MS). Los Alamos National Lab., NM (United States). 1996.
11. Dong C, Zhang PQ, Feng WQ, Huang TC. The sensitivity study of the modal parameters of a cracked beam. *Proc 12th Int Modal Anal*. 1994;2251:98.
12. Heylen W, Lammens S, Sas P. *Modal analysis theory and testing*. Belgium: Katholieke Universiteit Leuven, Faculty of Engineering, Dept. of Mechanical Engineering, Division of Production Engineering, Machine Design and Automation; c; 1998.
13. Armstrong DM, Sibbald A, Fairfield CA, Forde MC. Modal analysis for masonry arch bridge spandrell wall separation identification. *NDT E Int*. 1995;28(6):377-386.
14. Schoukens J, Pintelon R, Rolain Y. Time domain identification, frequency domain identification. Equivalencies! Differences? *P Amer Contr Conf*. 2004;1:661-666.
15. Schwarz G. Estimating the dimension of a model. *Ann Stat*. 1978;6(2):461-464.
16. Zhang L, Yao Y, Lu M. An improved time domain polyreference method for modal identification. *Mech Syst Signal Process*. 1987;1(4):399-413.
17. Zhang L, Wang T, Tamura Y. A frequency–spatial domain decomposition (FSDD) method for operational modal analysis. *Mech Syst Signal Process*. 2010;24(5):1227-1239.
18. Akaike H. A new look at the statistical model identification. *IEEE Trans Automat Contr*. 1974;19(6):716-723.
19. De Roeck G, Peeters B, Ren WX. Benchmark study on system identification through ambient vibration measurements. Proceedings of IMAC-XVIII, the 18th International Modal Analysis Conference, San Antonio, Texas. 2000; 1106–1112.
20. Allemang RJ. The modal assurance criterion—Twenty years of use and abuse. *J Sound Vib*. 2003;37(8):14-23.

21. Juang JN, Pappa RS. An eigensystem realization algorithm for modal parameter identification and model reduction. *J Guid Control Dynam*. 1985;8(5):620-627.
22. Vicario F, Phan MQ, Betti R, Longman RW. Output-only observer/Kalman filter identification (O3KID). *Struct Control Hlth*. 2015;22(5):847-872.

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