

Damage identification of structures using experimental modal analysis and continuous wavelet transform

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Abstract:

Modal analysis is a powerful technique for understanding the behavior and performance of structures. Modal analysis can be conducted via artificial excitation, e.g. shaker or instrument hammer excitation. Input force and output responses are measured. That is normally referred to as experimental modal analysis (EMA). EMA consists of three steps: data acquisition, system identification and modal parameter estimation. EMA, which is also known as frequency response function (FRF) testing, has been widely preferred for the modal parameter estimation of structures. The main objective of this paper is to determine the locations of damages by applying the wavelet transform to the measured mode shapes. The mode shapes are obtained from EMA by applying FRF of structure as the input data. In the present work, a two-stage method of determining the location of multiple structural damages on space structures is proposed. Firstly, EMA is applied to estimate the first mode shape of space structure by applying FRF as input data. In the second stage the mechanism of using 2D-CWT is applied by exploiting the concept of simulating the mode shape of space structure to a 2D spatially distributed signal for damage localization of space structure. Multiplicities of structural elements and joints are the main challenges related to damage detection of space structure. The validation of EMA is performed with modal assurance criterion (MAC). Seven numerical examples are conducted on two double layer diamatic domes with different sizes to assess the effectiveness of the proposed 2D-CWT method. The results demonstrate the reliability and applicability of the introduced method.

1. Introduction

Pioneering research in the field of damage detection started in the late 19th century with the realization that only visual inspection of damaged structures was not sufficient to maintain the reliability of structures (Cawley and Adams 1979). In the last decades the nondestructive examination techniques and the structural health monitoring techniques as well, have received a considerable amount of interest. Reliable nondestructive damage detection is essential for the development of structural health monitoring.

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Among nondestructive techniques, global vibration-based methods are necessary for damage localization of large and intricate structures. Vibration based SHM method is especially advantageous when compared with traditional SHM based on non-destructive testing methods, including ultrasonic wave (Sohn et al. 2014[43]), magnetic particle, eddy current testing (Nováková et al. 2015[32]) and X-ray (Bull et al. 2013[3]) etc., which require accessibility and measuring at any potentially damaged area. The difference between the calculated and measured responses of the structure, is the most efficient way for system identification in SHM (Mirzaee et al. 2015[30]). Modal parameters depend only on the mechanical characteristics of the structure and not on the applied excitation (Wei Fan & Pizhong Qiao 2011[49]).

Xiang and Liang (2012)[50] introduced a new method to detect the location of cracks in beam element by

applying the wavelet transform to the mode shape and using the measured natural frequencies as input data. The effectiveness of the proposed hybrid two-step method was demonstrated by numerical simulation and experimental investigation of a cantilever beam with two cracks.

Scanning Laser Doppler Vibrometers (LDV) are useful tools for non-contact vibration measurements with high resolution in a considerably small period of time. Siringoringo and Fujino (2009)[42] developed a modal-based damage detection method that uses ambient vibration and LDV for noncontact operational modal analysis of structural members. The system employs natural excitation technique to generate the cross-correlation functions from laser signals, and the eigensystem realization algorithm to identify modal parameters of structural members. The method was validated by an experimental work on cantilever plate.

Vibration-based damage detection methods make use of dynamic responses of a structure, like natural frequencies and mode shapes, and frequency response functions as well. Alterations in mode shapes have been considered by several researches for damage detection of structure. In the method introduced by Qiao et al. (2012)[34], frequency based features and time-frequency based features were extracted from measured vibration signals by Fast Fourier Transform and CWT to form one dimensional or two dimensional patterns, respectively. Results showed that features of the signal for different damage scenarios could be uniquely identified by these transformations, and suitable correlation algorithms could perform pattern matching that identified damage location.

Radzienski et al. (2011)[36] introduce a method for structural damage detection based on experimentally obtained modal parameters. Pandey et al. (Pandey et al. 1991[33]) introduced a curvature mode shape method as a possible candidate for identifying and locating damage in a structure. The results show that sudden changes in the curvature mode shapes is localized in the location of damage and can be used to detect damage in a structure. Genetic algorithm is applied by Maity et al. (Sanayei & Onipede 1991[41]) to detect the structural damage from changes in natural frequencies. They formulate the inverse problem in optimization terms and then utilize a solution procedure with genetic algorithm to assess the damage. Meruane used real-coded genetic algorithm method to detect structural damage. It addresses the set-up of the GA parameters and operators. The studies include different objective functions, which are based on frequencies, mode shapes, strain energy and modal flexibility (Meruane & Heylen 2011[29]). A methodology is presented by John B. Kosmatka (1999)[21] for detecting structural damage in structural systems. The procedure is based on using experimentally measured modes and frequencies in conjunction with vibratory residual forces and a weighted sensitivity analysis to estimate the extent of mass and stiffness variations in a structural system. The method is demonstrated by using a ten-bay space truss as an experimental test bed for various damage scenarios.

Xu et al. (2014)[52] experimentally explored the possibility of using the added stiffness provided by control devices and frequency response functions (FRFs) to detect

damage in a building complex. Scale models of a 12-storey main building and a 3-storey podium structure were built to represent a building complex. The experimental results showed that the FRF-based damage detection method could satisfactorily locate and quantify damage. Lee & Shin (2002)[24] introduced a FRF based structural damage identification method with two practical strategies. The first strategy is to obtain as many equations as possible from measured FRFs by varying excitation frequency as well as response measurement point. The second strategy is to reduce the domain of problem, which can be realized by the use of reduced-domain method introduced in this study. Mohan et al. (2013)[31] used the FRF with the help of Particle Swarm Optimization (PSO) technique, for structural damage detection and quantification. FRF is used as input response in objective function, and PSO algorithm is used to predict the damage. Efficacy of these tools has also been tested on beam and plane frame structures.

Golafshani et al. (2010)[11] presented a methodology which applies FRF data at some frequency points to arrive at perturbations to the stiffness matrix due to some defects in the structure. The method is demonstrated numerically on a spring mass system (shear building) and then applied to an offshore jacket platform. Salehi et al. (2010)[40] used both imaginary and real part of FRF shapes in the damage detection by applying the gapped smoothing method. A clamped aluminum beam model is used to generate numerical simulated FRFs for healthy and damaged states which are then put into proposed methodology. Li et al. (2015)[25] measured the impact force and acceleration responses from hammer tests and analyzed it to obtain the frequency response functions at sensor locations by experimental modal analysis to identify the damage of the slab.

In recent years, the use of wavelet analysis in damage detection has become an area of research. Alteration of the vibration characteristics of the structure, such as the natural frequency, displacement, mode shapes and damping ratios are signs to observe the damage in the structure (Gholizad & Safari 2016[10]). These features are crucial for structural health monitoring systems, including structural damage detection, localization and quantification (Hsieh & Halling 2008[19]; Wei Fan & Pizhong Qiao 2011[49]). Signal processing based methods are typified by Fourier transform (Quek et al. 2003[35]; Roveri & Carcaterra 2012[38]), wavelet transform (Hajizadeh & Salajegheh 2016[13]), time-frequency analysis (Hamzeloo et al. 2012[14]; Bharathi Priya & Likhith Reddy 2014[2]), and intelligent computation (Strang & Nguyen 1996[46]). Wavelet transform background goes back to the beginning of the last century (Haar 1910[12]), and its development as an engineering signal processing analysis tool for SHM is rather new (Surace & Ruotolo 1994[47]). The main advantage gained by using wavelets is the ability to perform local analysis of a signal which is capable of revealing some hidden aspects of the data that other signal analysis techniques fail to detect.

Performance of a wavelet analysis heavily depends on wavelet type, number of vanishing moments, scale and

translation parameters. A decentralized damage identification method using wavelet signal analysis tools embedded with wireless smart sensors has been proposed by Yun et al. (2011)[55]. Hoon et al. (2004)[18] used wavelet transform as a tool to detect changes in the response of a structure with an active sensing system to produce a near-real-time, online monitoring system. Wavelet-based methods have been applied by researchers for detection and localization of damages in one-dimensional structural parts (beams) (Zhong & Oyadiji 2011[56]; Xiang & Liang 2012[50]; Song et al. 2014[45]) and 2D plane problems (plate) (Gandomi et al. 2011[9]; He & Zhu 2015[15]).

The separability of compactly supported wavelets gives an opportunity to obtain 2D wavelets, which can enlarge the field of application for plane problems both in theoretical investigations and practical engineering tasks. Applications of 2D damage detection problems were proposed by Wang & Deng (1999)[48]. The crack location on a steel plate was detected by a variation of the Haar wavelet coefficients. The selection of an appropriate wavelet for damage detection is a crucial problem in the wavelet-based methods. Application of various wavelets to this problem analyzed their effectiveness based on the length of an effective support and the number of vanishing moments of a given wavelet were introduced by Rucka & Wilde (2006)[39]. Huang et al. (2009)[20] used Mexican Hat wavelet for 2D, and 3D (three-dimensional) wavelet transform for damage detection. The feasibility of the method is demonstrated using two illustrative examples: one is based on the crack-tip strain field of a plate subjected to bi-axial loads, and the other is based on the deflection field of a simply supported plate with defects subjected to static or impacting transverse loads. The results indicate that the damage positions are accurately located, and the damage severity is qualitatively assessed. Other similar studies with different types of 2D wavelets and algorithms have been proposed by researchers for detecting damage in plates (Douka et al. 2004[6]; Katunin 2011[22]; Gallego et al. 2013[8]; Yang et al. 2013[53]; Makki Alamdari et al. 2015[27]; Xu et al. 2015[51]). If an EMA is performed, then wavelet analysis can be applied to estimated mode shapes or their derivatives to detect changes induced by damage. It is successfully applied to beams and plates by researchers (Zhong & Oyadiji 2011[56]; Solís et al. 2013[44]; Xu et al. 2015[51]). Damage detection of truss like structures with limited number of elements have been studied by various methods (Yun 2012[54]; Rezaiee-Pajand & Kazemiyani 2014[37]). Space structures, which enable the designers to cover large spans as sports stadiums, assembly halls, exhibition centers, shopping centers and industrial buildings have been widely applied by structural and architecture engineers in the recent decades.

The main objective of this paper is proposing an applicable method for estimating the mode shape of structures for determining the location of damages on space structures by applying the wavelet transform to the measured mode shapes. We proposed a method where the mode shape of structure can be estimated by EMA

according to FRF obtained from the sensors installed at the nodes. FRF is calculated from dynamic response of structure. The mechanism of 2D-CWT is applied by exploiting the concept of simulating the estimated mode shape of space structure to a 2D spatially distributed signal for damage localization of space structure. Numerical results show the high efficiency of the proposed method for accurately identifying the location of multiple structural damages.

2. Theoretical Background

2.1 Experimental modal analysis

It is commonly known that the presence of damage influences vibration parameters of the examined component. One of vibration parameters very sensitive to damages is the mode shape. Measuring the mode shape characteristics of structure with proper accuracy was almost impossible in the past times. Recently, advanced technological devices, like scanning laser doppler vibrometer and wireless smart sensors, enable exact mode shapes properties with acceptable accuracy, in a short time (Lieven & Ewins 2001[26]).

Mode shape of intact and damaged space frame can be estimated according to the calculated FRF from dynamic analysis of space structure. FRF is applied as the input data to EMA. Line-fit method is employed for EMA as introduced by Kouroussi (Kouroussi et al. 2012[23]).

2.2 Frequency response function

A frequency response function implies the response of a structure to an imposed force as a function of frequency. The response can be displacement, velocity, or acceleration. The relationship between Force and Response demonstrates as follows

$$X(\omega) = H(\omega)F(\omega) \quad (1)$$

$$H(\omega) = \frac{X(\omega)}{F(\omega)} \quad (2)$$

Where $H(\omega)$ is FRF, $X(\omega)$ is response in frequency domain and $F(\omega)$ is external force presented in frequency domain. The FRFs are taken as the ratio of Fourier Transforms of the time domain response and input forces. One term in the series form of the frequency response function H_{ij} can be expressed as

$$H_{ij} = \frac{X_i}{F_j} = \sum_{k=1}^n \frac{B_{ijk}}{\omega_k^2 - \omega^2 + \eta_k \omega_k^2} \quad (3)$$

Where ω_k is the kth resonance frequency, ω is working frequency, η_k is the kth modal damping loss factor and B_{ijk} (modal constant) are the modal parameters of mode k. H_{ij} is the term of FRF that relates to impact at point j and response at point i. n is the number of natural frequencies considered for calculation of FRF. These methods exploit interesting properties of a FRF like the circularity in the immediate vicinity of resonance or the linearity of inverted FRFs, which are associated to important statement in modal analysis theory.

Space structure has large number of nodes and elements. Practically, installation of sensor in all nodes of

space structure is impossible and extremely costly. In this study, sensors are installed in the nodes of top layer in the checkered form to access the variations in the response data of damaged structure in compression to complete one in all areas of space frame.

To evaluate the accuracy of applied EMA method, analytical modal analysis is performed and the modal assurance criterion (MAC) is used which can be computed as:

$$MAC_k = \frac{|\phi_k^{mT} \phi_k^{calc}|^2}{(\phi_k^{mT} \phi_k^m)(\phi_k^{calcT} \phi_k^{calc})} \quad (4)$$

Where ϕ_k^m and ϕ_k^{calc} denote the modal vectors obtained from an EMA and analytical model, respectively. The subscripts k, denote the orders of the modes; and the superscript T, denotes the transpose of a vector. The damage is simulated in analytical model by diminishing Young's modulus of elements in the damaged region located in the previous step.

2.3 Theory of wavelet transform

Wavelet analysis provides a powerful tool to characterize the local features of a signal. Unlike the Fourier transform, where the function used as the basis of decomposition is always a sinusoidal wave, other basis functions can be selected for wavelet shape corresponding to the features of the signal. These basis functions are named mother wavelet. A mother wavelet is a real or complex-valued function $\psi(x) \in L^2(R)$ of zero average and finite length. $L^2(R)$, denotes the Hilbert space of measurable, square-integrable one-dimensional functions (Mallat 2008[28]).

$$\int_{-\infty}^{+\infty} \psi(x) dx = 0 \quad (5)$$

This can be dilated or compressed with a scale parameter a, and translated by a position parameter b as follows:

$$\psi_{a,b}(x) = \frac{1}{\sqrt{a}} \psi\left(\frac{x-b}{a}\right) \quad a > 0, b \in R \quad (6)$$

The wavelet transform of $f(x) \in L^2(R)$ at the scale a and position b is computed with continuous wavelet transform defined as follows:

$$Wf(a, b) = \langle f, \psi_{a,b} \rangle = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(x) \psi^*\left(\frac{x-b}{a}\right) dx \quad (7)$$

where $Wf(a, b)$ is called a wavelet coefficient for the wavelet $\psi_{a,b}(x)$ and measures the variation of the signal in the vicinity of a whose size is proportional to b and ψ^* is the complex conjugate of the mother wavelet function ψ .

When using the wavelet for signal analysis, if the scale parameter a is small, it results in very narrow windows and is appropriate for high-frequency components in the signal $f(x)$. On the other hand, if the scale parameter a is large, it results in wide windows and is suitable for the low-frequency components in the signal $f(x)$. The greater the scale is, the more detailed the frequency division is.

2.4 Two-dimensional continuous wavelet transform

The two-dimensional CWT (2D-CWT) is a natural extension of the one-dimensional CWT, with the translation parameter being a vector in the plane. As in the

1D case, a 2D wavelet is an oscillatory, real or complex-valued function $\psi(\vec{x}) \in L^2(R^2, d^2\vec{x})$ satisfying the admissibility condition on real plane $\vec{x} \in R^2$, $L^2(R^2, d^2\vec{x})$ denoting the Hilbert space of measurable, square integrable 2D functions on the plane. If ψ is regular enough as in most cases, the admissibility condition can be expressed as:

$$\psi(\vec{0}) = 0 \Leftrightarrow \int_{R^2} \psi(\vec{x}) d^2\vec{x} = 0 \quad (8)$$

Function $\psi(\vec{x})$ is called mother wavelet and usually localized in both the position and frequency domains. The mother wavelet ψ can be transformed in the plane to generate a family of wavelet $\psi_{a,\vec{b},\theta}(\vec{x})$. A transformed wavelet $\psi_{a,\vec{b},\theta}(\vec{x})$ under translation by a vector \vec{b} , dilation by a scaling factor a, and rotation by an angle θ can be derived as (Rucka and Wilde 2006[39]):

$$\psi_{a,\vec{b},\theta}(\vec{x}) = a^{-1} \psi\left(r_{-\theta}\left(\frac{\vec{x}-\vec{b}}{a}\right)\right) \quad a > 0, \vec{b}, \theta \in R^2 \quad (9)$$

Given a 2D signal $f(\vec{x}) \in L^2(R^2, d^2\vec{x})$, its 2D-CWT (with respect to the wavelet ψ) $Wf(a, \vec{b}, \theta)$ is the scalar product of $f(\vec{x})$ with the transformed wavelet $\psi_{a,\vec{b},\theta}$ and considered as a function of (a, \vec{b}, θ) as:

$$Wf(a, \vec{b}, \theta) = \langle f, \psi_{a,\vec{b},\theta} \rangle = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(\vec{x}) \psi^*\left(r_{-\theta}\left(\frac{\vec{x}-\vec{b}}{a}\right)\right) d^2\vec{x} \quad (10)$$

where the ψ^* denotes the complex conjugate and $r_{-\theta}$ is the 2D rotation matrix as:

$$r_{-\theta} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \quad (11)$$

The 2D-CWT is a space scale representation of a plane and acts as a local filter with scale and position. If the wavelet is isotropic, there is no dependence on angle in the analysis. The Mexican hat wavelet is an example of an isotropic wavelet. Isotropic wavelets are suitable for point wise analysis of a 2D system. If the wavelet is anisotropic, there is a dependence on angle in the analysis, and the 2D-CWT acts a local filter with scale, position, and angle. The Morlet wavelet is an example of an anisotropic wavelet. In the Fourier domain, this means that the spatial frequency support of the wavelet is a convex cone with the apex at the origin. Anisotropic wavelets are suitable for detecting directional features.

The point wise nature of the 2D damage detection in the space structure has made the isotropic wavelets suitable for this kind of structure. The chosen wavelet function is isotropic Mexican hat wavelet, and the scaled is equal to 2. Wavelet computation is performed using MATLAB code. The denoising and filtering capability of the isotropic 2D-CWT provides us with an important analysis tool in practice. The Mexican hat wavelet is real and isotropic. The 1D Mexican hat wavelet is the second derivative of the Gaussian function, as shown in Fig. 1. Likewise, the 2D Mexican hat wavelet is the Laplacian of the 2D Gaussian function. It was first proposed by Hildreth (1984)[16] as a differential-smooth operator for their edge contours detection theory. Its expression in the position domain is (Fan & Qiao 2009[7]):

$$\psi(\vec{x}) = (2 - |\vec{x}|^2) \exp\left(-\frac{1}{2} |\vec{x}|^2\right) \quad (12)$$

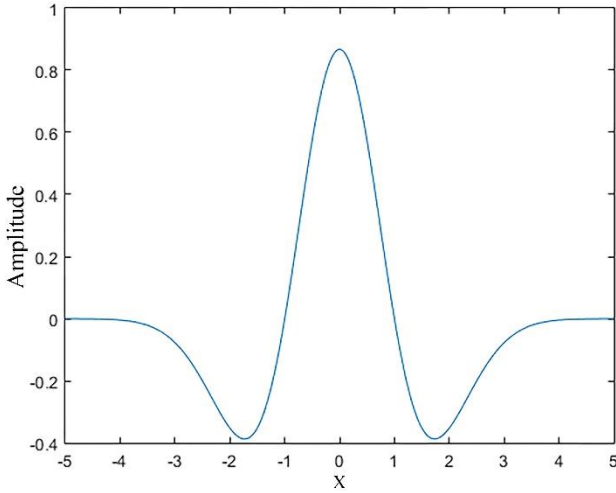


Fig.1: Mexican hat mother wavelet

3. Method

In the present section, the structure of proposed method for damage detection of space structure is described. First, EMA technique is applied to estimate the first mode shape of intact and damaged structure. The measured FRF of structure is considered as the input data for EMA. Second, 2D-CWT technique is employed to the isosurface of intact and damaged first mode shape on (x, y) plane to reveal the location of damage. Finally, the effectiveness of the proposed method for damage detection of space structures will be evaluated by applying on introduced space frame.

Step 1. Estimating mode shapes of structure

First of all, the geometric pattern of space structure is created using Formian software. Secondly, the modified geometric pattern is analyzed by SAP2000 and truss elements cross section are designed according to the LRFD AISC (1999)[1]. At the end, the open-source finite-element package Opensees is used to perform the dynamic analysis by applying a sinusoidal external force at the nodes of top layer. Vertical displacement of each node of top layer is measured. A MATLAB code is written and the FRF of nodes is calculated from the dynamic response of structure by imposing the sinusoid load in the frequency range from zero to 200 Hz with 0.5 Hz step. The load is imposed in node j and the response is measured in node i to calculate the H_{ij} term of FRF. The introduced EMA method is used to calculate the mode shapes of the intact and damaged structures. Analytical modal analysis is performed by Opensees to evaluate the accuracy of applied EMA method according to the MAC introduced in Eq. 4.

Step 2. Generating isosurface

The three-dimensional coordinate of nodes need to be decreased to a two-dimensional plain to employ 2D-CWT. Therefore, the isosurface of joints on (x, y) plane is created by applying the values of estimated mode shapes of nodes. Isosurface is the image of nodes coordinate on (x, y) plain and the values of z coordinate is set to be zero. Coordinate of joints and outline shape of isosurface is determined according to the geometric features of

structure. The isosurface is reshaped to be rectangular by assuming zero values for empty arrays and the arrays outside real shape of isosurface. Finally, zero arrays of isosurface matrix are replaced by values from linear interpolation. The generated isosurface $f(\vec{x})$ can be directly used to indicate the location and area of the damage.

Step 3. 2D-CWT analysis

In practice, this could be verified by observing that the natural frequencies and mode shapes of the structure are not drastically changed after the damage imposing event. Wavelet transforms are a mathematical means for performing signal analysis. The specific properties of wavelet analyses on diagnosing changes in signal makes them useful tools for damage detection through application of signal processing. The 2D-CWT is implemented in MATLAB to the modified isosurface. Once the 2D-CWT is computed, we face a problem of visualization of wavelet coefficients because $Wf(a, \vec{b}, \theta)$ is a function of four variables: its position (x, y) , scale a , and angle θ . Since the isosurface in this study is oriented in x - and y -directions, the most effective angle θ for our damage detection algorithm should align with x - or y -axis, i.e., $\theta = 0$ or $\pi/2$. Hence, for simplicity, the variable θ is fixed at $\theta = 0$ in this study.

Step 4. Boundary distortion and noise effect treatment

In the wavelet base damage detection methods, researchers always face two main problems of boundary distortion and noise effects. The wavelet coefficients will be inevitably distorted by the discontinuity of mode shapes at their ends and could reach an extremely high/low value near the boundaries, where there is no possibility for damage to occur. A two-step method is applied to alleviate the distortion of coefficients caused by the boundary condition and noise effects. Firstly, the mode shape data is extended beyond its original boundary by the cubic spline extrapolation based on points near the boundaries (Fan and Qiao 2009). Secondly, the noise effects of EMA and 2D-CWT are treated by calculating the absolute difference values of wavelet coefficients derived from 2D-CWT analysis of intact and damaged structure as (Castro, García-Hernandez et al. 2006; Gallego, Moreno-García et al. 2013):

$$D(\vec{x}) = |Wf_a - Wf_d| \quad (13)$$

where Wf_a and Wf_d are the 2D-CWT coefficients of intact and damaged space structure respectively. Finally by plotting the isosurface of $D(\vec{x})$ values, location and area of the damage can be defined.

4. Application Examples

In this study, the double-layer diamatic dome is considered to evaluate the applicability of introduced multiple structural damage detection method. Two different sizes of dome structure are considered to evaluate the accuracy of method in various size of space structures.

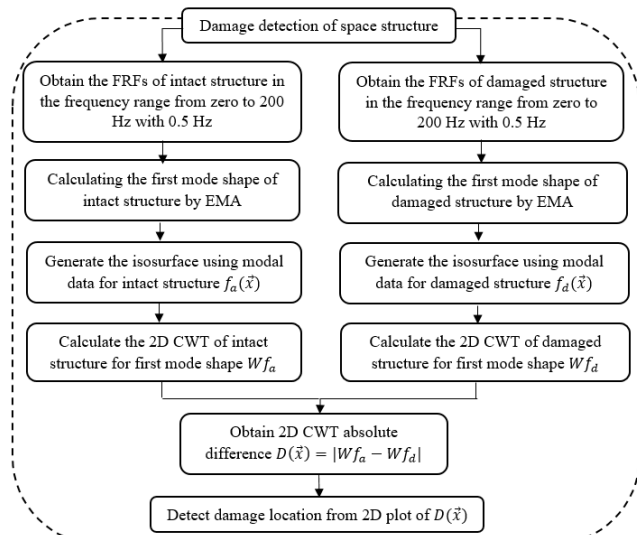


Fig.2: diagram of damage locations detection

Space Structure consists of steel truss elements (tubular part) and connectors (ball joint). MERO jointing system is the most common type of ball joint. MERO joint consists of a ball with hot-pressed steel forging material and flat sides with tapped holes in the center of each side if necessary. Tubular parts include a cone-shaped steel welded at both ends, which house connecting steel bolts. Bolts are tightened by means of a hexagonal sleeve and dowel pin arrangement. The details of the MERO jointing system is shown in Fig. 3. Up to 18 tubular members are connected together at various angles. The axes of members pass through the center of the ball and eliminate the eccentricity of loads at the joint. Thus, the joint is only under the axial forces. In a double-layer space structure, the ball joint system can be subjected to tension or compressive axial forces. Then tensile forces are carried along the longitudinal axis of the bolts and resisted by the tubular parts at the end of cones. In the mechanism of MERO joint, the compressive forces do not produce any stresses in the bolts; they are distributed to the node through the sleeves.

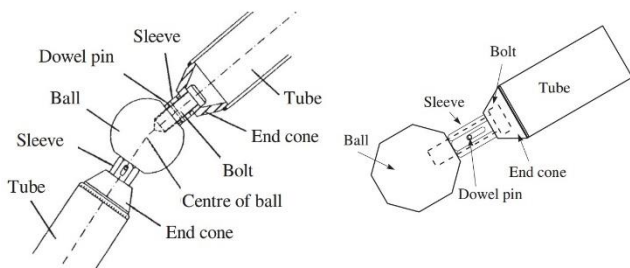


Fig.3: MERO jointing system with two tubular elements

According to step one, a three phases design procedure is implemented to perform an eigenvalue analysis and dynamic time history analysis to calculate the analytical mode shapes and FRFs of space frame, respectively. The programming language Formian is utilized to create the polyhedral configuration of space frame, including node coordinates. The outcome geodesic form of space frame is exported to SAP2000. The general view of selected space frames in SAP2000 are depicted in Fig. 4. Geometric

properties of introduced double layer diamatic domes are illustrated in Table 1.

Table 1. The structural properties of sample systems

Type	Property	Value (unit)
A	Radius of top circum sphere	12 (m)
	Radius of bottom circum sphere	11 (m)
	Sweep angle	40
	Frequency of top layer	6
	Number of sectors	4
	Number of elements	867
B	Number of joints	229
	Radius of top circum sphere	50 (m)
	Radius of bottom circum sphere	48.5 (m)
	Sweep angle	40
	Frequency of top layer	16
	Number of sectors	6
Number of elements	9216	
Number of joints	2352	

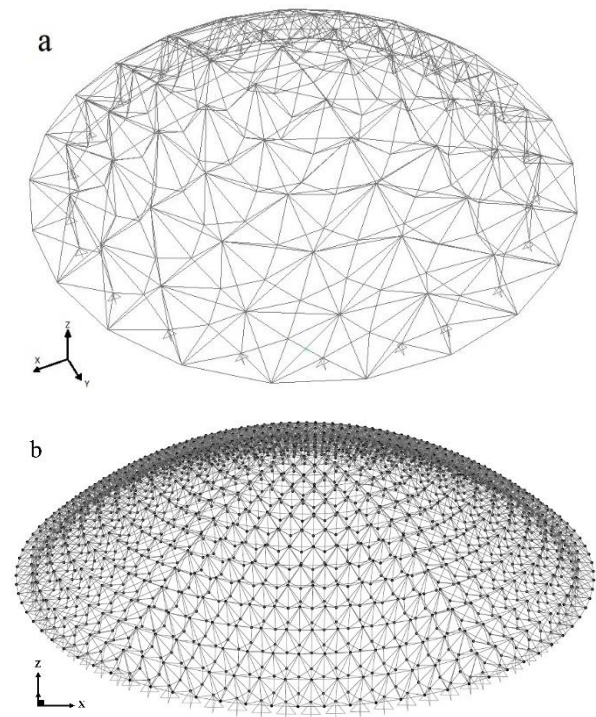


Fig.4: General view of the double-layer diamatic dome, (a) Diamatic dome type A, (b) Diamatic dome type B

In the second step, imported geometric data in SAP2000 is exploited to design the tubular parts. It is assumed that tubular part has uniform area and material properties along its length. Beam element applied for tubular parts with modulus of elasticity $E = 200 \text{ kN/mm}^2$, density $\rho = 8000 \text{ kg/m}^3$, yield stress 0.25 kN/mm^2 and the Poisson's ratio $\mu = 0.3$. The designed pipe sections for tubular parts of double layer space structures are shown in table 2.

Table 2. Cross-section properties of tubular parts of double layer space structures

	Outside diameter (cm)	Wall thickness (cm)	Cross-Section area (cm ²)	mass per miter length (kg)
P30	3	0.28	2.39	0.192
P40	4	0.3	3.49	0.279
P55	5.5	0.35	5.66	0.453
P70	7	0.35	7.31	0.585
P80	8	0.4	9.55	0.764
P90	9	0.5	13.35	1.068
P100	10	1	28.27	2.263

The illustrated pipe sections in table 2 are modeled by one-dimensional frame element with three degrees of freedom at each of its two nodes and designed according to the LRFD AISC (1999)[1] provision. In the last step, the designed section properties of tubular parts and geometric properties are imported from SAP2000 and used to carry out the set of modal analyses in the open-source finite-element package Opensees. The analytical Opensees model, consists of nodes coordinate, material properties and section assignments.

Uniaxial bilinear steel material is assigned for tubular parts with the same material properties introduced in the previous step and strain-hardening ratio 0.05. Uniaxial Section is applied to define the section properties of tubular parts according to axial force-deformations curve, cross-section area and mass per unit length value.

Opensees is used as explained in step one to perform an eigenvalue and dynamic analyses to calculate the mode shapes and FRFs of both intact and damaged space structures respectively. The isosurfaces of first natural frequency with equal elevation on (x,y) plane for EMA of sample systems are illustrated in Fig. 5.

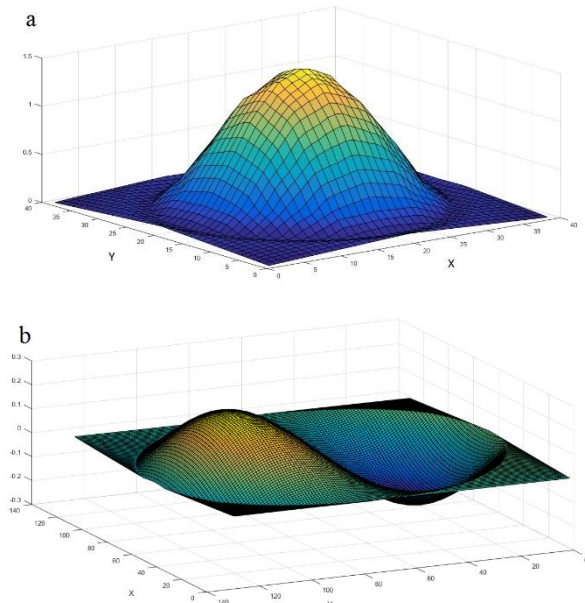


Fig.5: Isosurface of the first natural frequency for experimental modal a) Diamatic dome type A, b) Diamatic dome type B

The accuracy of applied EMA method is assessed by MAC in Eq. 4 and the results for the first mode shapes are presented in table 3.

Table 3. MAC for EMA of introduced models

Model type	First mode shape
A	0.9941
B	0.9984

The 2D-CWT analysis with Mexican hat mother wavelet is exploited to the isosurface generated by the experimental mode shape. Damage usually causes a reduction in the local stiffness of the structures. One option is to model this damage in stiffness of element by reduction in Modulus of Elasticity. This equivalent modeling approach is often sufficient for the identification of local damage (Homaei et al. 2014[17]). Damage can be simulated in the ball joint by a reduction in the stiffness of all its connected tubular parts. Four damage scenarios are selected to evaluate the applicability of introduced method as illustrated in table 4.

Table 4. Damage scenarios of sample systems

Model type	Scenario No.	Damaged elements number	Damaged Joints number
A	1	-	20
	2	251	-
	3	37 236	-
	4	227 228	-
B	5	5317 6391	-
	6	6392 6358	-
	7	-	2290 1530

The introduced scenarios are selected to evaluate the ability of proposed method to detect multi-damage in joints and tubular parts of space frames.

Mexican hat wavelet is used to decompose the isosurface of the first experimental mode shape of intact and damaged systems. The 2D wavelet coefficients of intact and damaged space frames for introduced scenarios are illustrated in Figs 6 and 7.

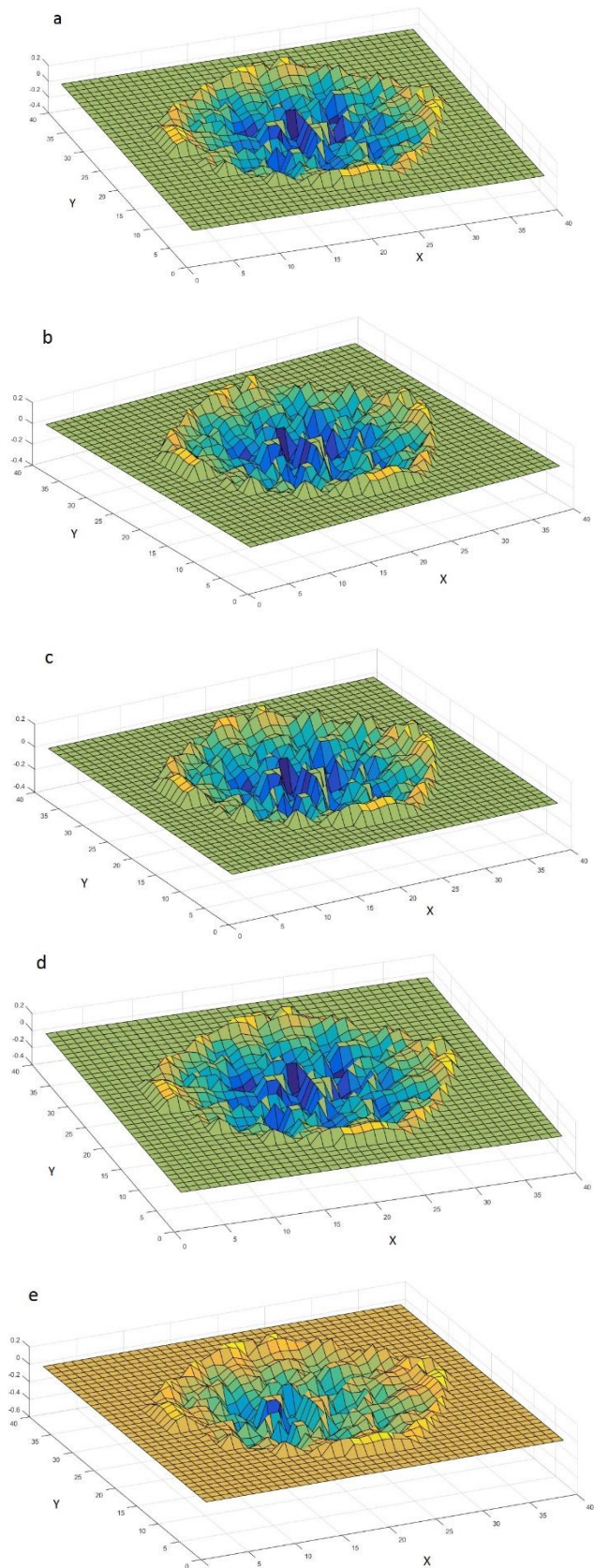


Fig.6: (a) 2D-CWT for the intact isosurface of type A dome structure; 2D-CWT for the damaged isosurface of type A dome structure (b) Scenario 1;(c) Scenario 2;(d) Scenario 3; (e) Scenario 4

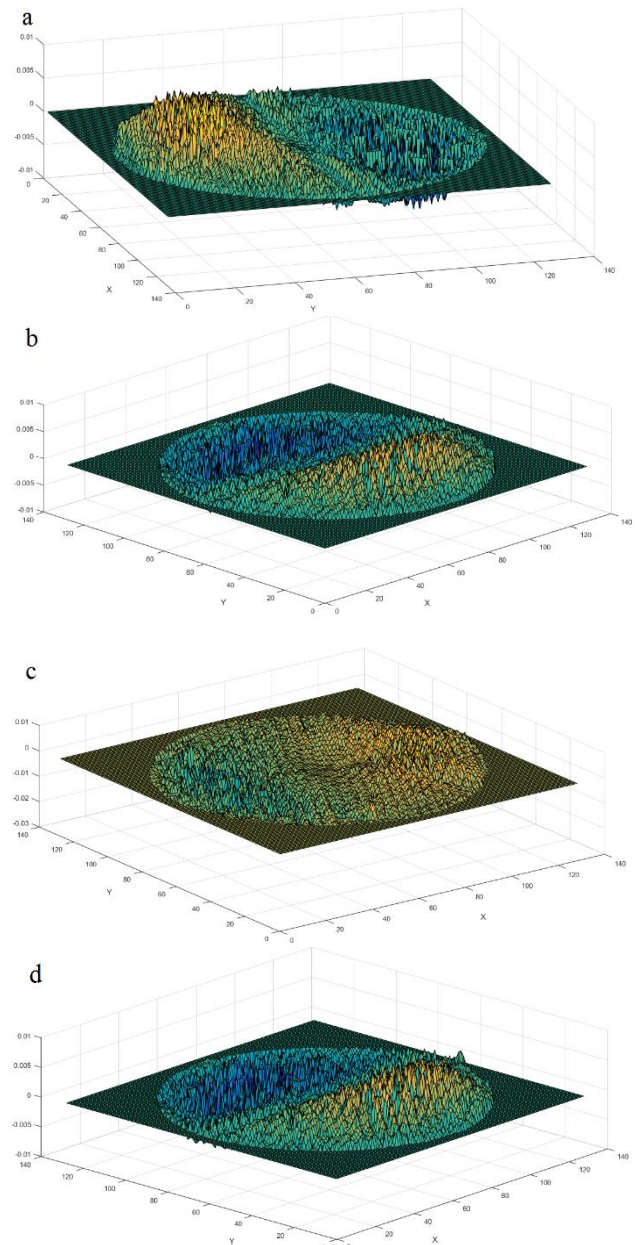


Fig.7: (a) 2D-CWT for the intact isosurface of type B dome structure; 2D-CWT for the damaged isosurface of type B dome structure (b) Scenario 5;(c) Scenario 6;(d) Scenario 7

According to the above graphical results, the location of damage is unclear in the noisy pattern. Damage index $D(x,y)$ is employed from Eq. 13 to decrease the noise effects of EMA and 2D-CWT as explained in step 4 and the results are plotted in Figs 8 and 9.

Figs 8 and 9 show the smoothed surface for the applied damage scenarios depicted in table 3. The results demonstrate the applicability of proposed method for multi-damage detection in elements and nodes of space structure.

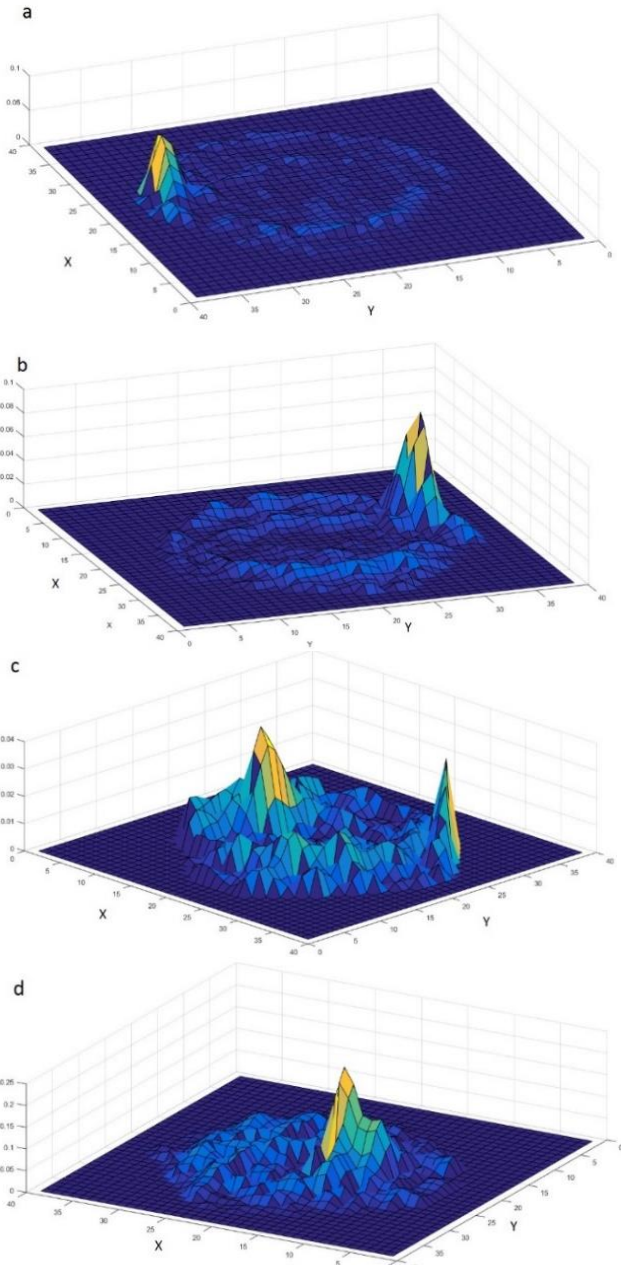


Fig.8: Damage index for the first mode shape of Type A dome structure: (a) Scenario 1; (b) Scenario 2; (c) Scenario 3; (d) Scenario 4

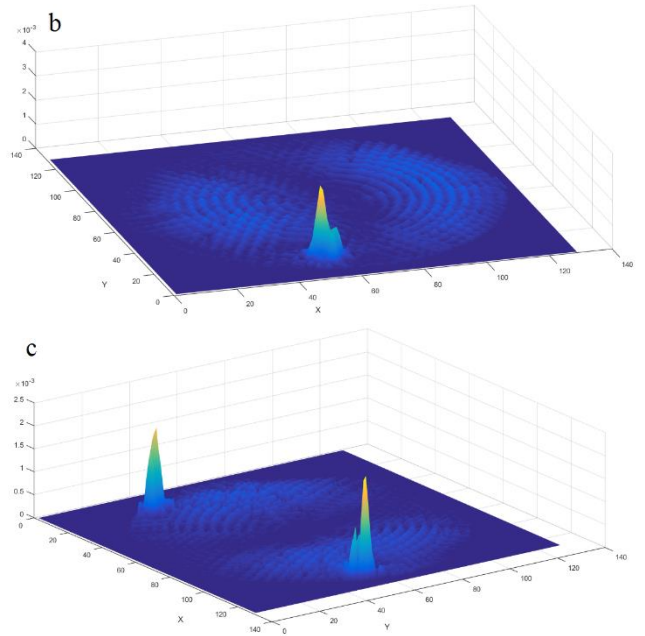
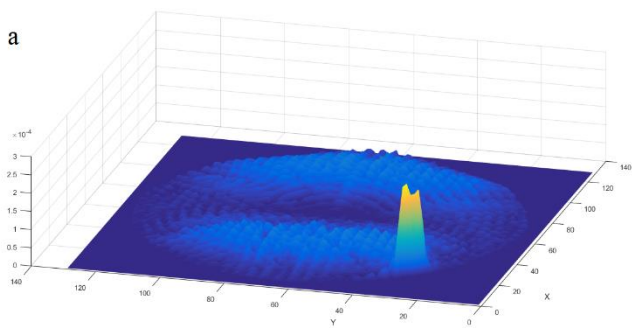


Fig.9: Damage index for the first mode shape of type B dome structure: (a) Scenario 5; (b) Scenario 6; (c) Scenario 7

5. Conclusions

This paper presents an EMA method based on FRF for measuring the mode shape of space structure to determine the locations of damages by applying the wavelet transform to the measured mode shapes. The mechanism of 2D-CWT is applied by exploiting the concept of simulating the experimental mode shape of space structure to a 2D spatially distributed signal called isosurface. The peaks or sudden changes in the isosurface are associated to the damage locations. Boundary distortion and noise effect of EMA and 2D-CWT are diminished according to step 4.

In order to evaluate the accuracy of the proposed method for damage detection of space structures, seven illustrative examples are considered in two different sizes of diametric double layer dome.

The damage scenarios are selected intentionally to evaluate the applicability of method in elements and nodes of space structure for different possible cases of damages. The numerical results reveal that the combination of the 2D-CWT algorithm together with EMA is a Fast and accurate technique for multiple damage detection of space structures that is free from the size and geometrical properties of structure.

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