A novel approach of Structural Health Monitoring by the application of FFT and wavelet transform using an index of frequency dispersion

Fragkiskos P. Pentaris[1], John Stonham[1], John P. Makris[2]

Abstract — Monitoring the state of a structure provides the ability to anticipate structural failures and secure the safe use of a structure. The ability to reveal valuable information from the monitoring data is many times difficult and without result due to the fact that there are many limitations in terms of defining when a structure becomes inappropriate for use, when the data reveal damage, when the structural response of a structure has non-linear characteristics which could hide damage. This work suggests a novel approach in structural health monitoring by measuring the dispersion of the fundamental frequency of a structure. We apply fast furrier transform and wavelet transform in SHM data and proposed a novel index, which measures the dispersion of the building's fundamental frequency. This approach focuses on the frequency dispersion and presents its variability with and without structural damage and try to reveal non-linear characteristics of SHM data from a building under seismic or man-made excitation in order to work as an index of a probable structural damage. The suggested approach is applied in recorded accelerometer data, from a wired SHM network established in two neighbouring buildings of different age in the city of Chania, in Crete. The recording data were created by seismic activity, weather conditions and man-made activity.

Keywords — digital signal processing, structural health monitoring, acceleration recordings, wavelets, Fast Fourier Transform.

I. INTRODUCTION

DIGITAL signal processing enables us to analyze and distinguish signals in discrete recordings. Structural Health Monitoring (SHM) is an open issue which exhibits many technological and scientific challenges, like sensors which will be able to detect damage, low cost, high scalability, despite the big evolution yielded the last decades in parts of data processing, wireless protocols, autonomy and data rate analysis [1-4]. Revealing possible structural damage from recordings requires appropriate algorithm which will be able to extract reliable information determining the response of the structure under excitation, and discard useless man-made or environmental noise, and extract data which will define the response of the structure under excitation.

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II. DIGITAL SIGNAL PROCESSING METHODOLOGIES ON STRUCTURAL HEALTH MONITORING

A. Literature review of detection methods of on Structural Health Monitoring

Structural health monitoring (SHM) is the procedure for the detection and characterization of damage to structures or buildings. Due to authors Worden et al. [5] damage is defined as the change in either the material or the characteristics and structural properties of a structure, and could affect its structural response when there is excitation. They suggest that damage identification is a sum of four parts which conclude "the existence of damage, the damage locations, the types of damage, and the damage severity".

The methods of detection and location of damages in buildings are discussed in detail by Doebling et al. [6]. They categorized the identification methods first on the type of data that are measured and second depending the technique which is used for the identification of the damage, from the data that have been measured. They refer the method of frequency change, where the damage detection is based in the shifts of natural frequency of structures of systems, methods of studying the changes in mode shape, where there is the ability of localization of structural damage by determining modes shapes before and after damage. Different approach of mode shapes is by studying the mode shape derivatives like curvature etc. Beams are related with curvatures and strain with the relation:

$$\varepsilon = \frac{y}{R} = ky$$

where the strain is ε, the curvature radius R and k the curvature.

Author Doebling et al [6] also refers the "based on dynamically measured flexibility method", "matrix update method", "non-linear method" and "neural-network based method" as methods for damage identification by vibration response.

SHM methods are presented by Sohn et al. [7], where the sensing technologies, like strain, displacement, acceleration, are presented, as well as the feature that each method uses for SHM, like resonant frequencies, frequency response functions, modal shapes, damping, non-linear features etc. They indicate that the dependency on pre-defined analytical models has significant uncertainties and are not fully validated by the experimental data. In addition, no one of the reviewed research verified the numerical models or quantified the associated uncertainties in order to employ those models for damage detection. A key-problem to deal with is how the damage identification can be achieved over operational and environmental variability as well as when non-linear response introduced into the system. Approaches like statistical process control or simple hypothesis testing identify the existence and location of damage but cannot identify the type and the magnitude of the damage. Artificial neural network (ANN) approach needs training and damage data as input. The author also states that while the frequency of a structure is analog with its stiffness and the change in frequency displays change in stiffness, presents in the following figures the experiment I-40 Bridge over the Rio Grande in New Mexico, USA where there is change in fundamental frequency related to the reduced stiffness but this is not analog.

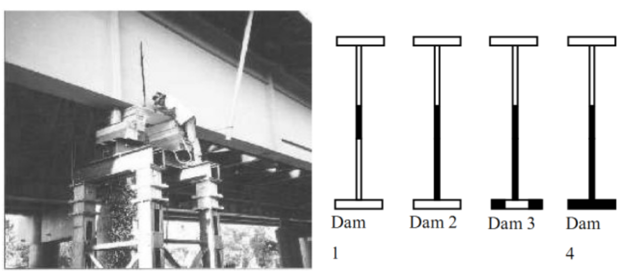

Fig.1 *Damage Detection Study of the I-40 Bridge over the Rio Grande in New Mexico, USA. Left figure: electric saw cutting cause damage in the bridge girder right figure: The levels of introduced damage in the girder (the shaded area is the reduced cross-section[7].*

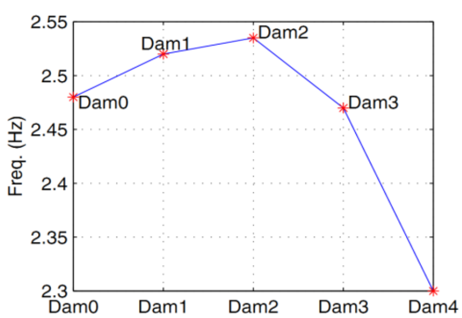

Fig.2 *The change of fundamental frequency on I-40 Bridge related to the damage levels presented in Figure 2.4[7]*

Hou et al. [8] test vibration signals with Wavelet Transform (WT) method. They investigate the noise intensity and damage severity of a building but they don't locate the point of the damage. Even when the severity of the damage is referred they cannot argue on which degree this reduces the stiffness of a building and affects its integrity or response. But they point out the need of further study to justify the results.

At a next publication, Hou et al. [9] apply again wavelets and they present the application of a model in non-linear, time-variant systems but there is no discussion on the localization of damage in a complex structure , or the detection of local change-lack of stiffness of a structure.

Taha et al. [3] examine wavelet transform, wavelet multi-resolution analysis and wavelet packet transform in analysis of signals from structures under excitation. They claim that although above methods provide damage detection, when these methods are combined with ANN the results are improved. ANN have been discussed by Fang et al. [10] where they implemented and compared Dynamic Steepest Descent (DSD), Fuzzy Steepest Descent (FSD) and Tunable Steepest Descent (TSD) learning rate algorithms demonstrating their limitations and merits. Although damage detection is enabled, these algorithms were applied in model structures and not real ones. Furthermore the system needs training in order to be effective, which means that it would learn in a real damage of a structure in order to be able to reveal possible damage in the future.

The methods of measuring the changes in resonance frequency of a system are very practical due to the high reliability of the results and the fast process of the recordings. The minimization of natural frequency indicates the reduce of stiffness and respectively high frequency reveals higher stiffness of a structure [11]. The same author presents that on models or real scale structures with cracks, structural failures, overload which caused damage, there was change in fundamental frequencies related with the undamaged condition. In the ease of measurement and the characteristic of global parameter of the natural frequency in a structure, also agree Sayyad and Kumar [12] where they try to assess the location and size of crack in a beam. They study the natural frequencies in an un-damaged and a damaged beam with the method of finite element in order to define the crack size and location by an inverse way. They present that crack could be defined like a spring which connects the parts of the beam and apply a model to relate natural frequencies with crack characteristics. Authors claim that the prediction of the crack with the reality of the crack, comes very close, but this is an experimental model where they apply it on reverse. In order to be more realistic they should apply in real structures also, in order to observe if this model follows the same principle, because the experimental models usually differs a lot from the real structures.

Frequency response functions (FRFs) have been applied by Salehi et al. [13] with two methods, independent component analysis (ICA)(method of separating a mixed signal to a set of source signal), and operational deflection shapes (ODSs) (method of visualizing the vibration pattern of a structure under excitation by an external force) in order to detect and also localize damage. Author presents that, except the FRFs data of the pre-damage and damage structure, there isn't the need of analytical model, in order to localize damage.

Experiment of frequency-based technique is presented by Esfandiari et al. [14] where they consider that natural frequency is related with stiffness reduction, for accuracy in results the mode shape of a structure in damaged and intact state are related with a linear combination, and they apply the method on two models in lab. They claim that the mode shape changes through the proposed algorithm are efficient without the need of intact structure model.

Vibration frequencies of damaged and undamaged states used by Goldfeld and Elias [15] proposing a “direct identification procedure” for the changes and dispersal of rigidity in a beam. They identify the problem of high number of unpredictable coefficients and face it with specific polynomial and the exact element method. The proposed procedure, although present the damage distribution in a beam, is verified only under specific conditions and in data from the literature which decrease the validity of the method for other structures and/or structural states.

Popescu [16] refers that in order to describe the response of buildings that are affected by high dynamic loads it needs non-stationary spectral analysis techniques. The time analysis, of the frequency analysis alone, is not able to reveal the characteristics of those dynamic loads which affect a structure. The author also presents methods that are applied in structural monitoring and could probably be applied in earthquake engineering, like short time frequency analysis (STFT). They indicate that STFT although has is very simple time-frequency analysis has the big disadvantage of limitation that time-resolution and frequency resolution function inversely to each other.

The author Zain et al. [17] applies wireless SHM system on a concrete bridge, monitoring the vibration data of the specific structure and after analysis, extract the mode shape of the bridge. They propose this mode shape data as a modal method for detection of damage in a structure.

ANN and WT have also been addressed by Shi et al. [18] where they discuss and apply a hybrid wavelet - neural network method to a benchmark structure. They use WT as neural network input achieving to reduce noise, and with ANN (pattern recognition) damage detection is performed in the lab. The damage detection has high accuracy (95 to 96% for the damage patterns under test) but this is not repeated with real structures, or with more damage patterns.

Lin and Qun [19] study variation of statistical parameters of vibration signals in time-domain, in order to achieve damage diagnosis with artificial neural network. Their experiment is on data monitored by bridge artificially excited. The architectures TNN (task negative network) and TDNN (time delay neural network) were tested with TDNN having better performance in terms of time and training process. Although they found some interest results, they need specific statistical parameters (which in other structure may not be efficient) and specific network architecture, for the prediction of damage in the tested bridge.

Xing et al. [20] use WT to study a bridge model and investigate the extent and time occurrence of pounding (for each frequency) in the specific tests, but they clearly indicate the need of further experimental studies on more practical (real) cases.

Autoregressive moving average (ARMA) model applied by bao et al. [21] for monitoring the structural health of a subsea pipeline. They analyze acceleration signals from the located on the pipeline sensors, normalize the data and apply auto-correlation function for reducing the noise effect. They also use partial autocorrelation function (a method for the identification of the lag in an autoregressive model (AR)) in order to define the best AR model order. The produced AR coefficients reveal the damage induced in the system. The method is applied in submarine pipeline under the effect of the force of waves and the author presents interesting results in the detection and localization of damage, but this is a specific system and a subsea system is different from a building or other structures, and the same principles (wave forces) may not occur in other states of structures like buildings (also the earthquake activity is completely different of the ambient wave force).

Xu et al. [22] face the errors of measurements and modeling in SHM damage detection methods by a stochastic method where they calculate before and after the damage the probability density functions (PDFs) of stiffness in a structure, and they compute a specific probability function with the measured PDFs in order to present the damage location and severity. They find the stiffness parameters of PDFs in a structure with and without damage occurrence, and compute the probability function:

$$P\{(K^u - K^d) \geq a \times K^u\}$$

where K^u the stiffness before damage and K^d stiffness after damage and a index which takes values from 0% until 100%, in order to depict the location and the harshness of damage.

Another one method much simpler for the revealing of cracks in beams is referred by Lee et al. [23] where again the problem is inverse and the solution is given by the application of Newton-Raphson technique. Authors model the crack as a rotational spring and using finite element method they relate the crack with a stiffness matrix, and finally iterate the location and size of the crack by the above method. According to the authors at the specific proposal method the real and the modeled cracks come very close. Finite element model is also used by Goldfeld et al. [24] with the combination of vibration frequencies and modes in order to locate and quantify damage. Although the prediction of mode shapes and bending stiffness is presented as reliable, they indicate that theory with reality differs, and many mode shapes are need in order to reliably define stiffness distribution.

Fast Orthogonal Search (FOS) has been applied by El Shafie et al. [25] where they apply this method to the IASC-ASCE SHM benchmark structure. They suggest that FOS is a non-linear modeling technique which provides high resolution spectral analysis and is able to reveal functional expansions in SHM data. FOS is able to detect critical frequencies in spectra better than FFT when the time-window of the data is less than 10 sec but for bigger time-windows in data analysis there are detection limitations. Thus, for small window analysis, FFT cannot reveal the frequencies that FOS does. On the other hand, FOS limitation is that background noises being removed sometimes could contain critical frequency information.

Performance of mono-bit DFT and quantization of the time signal have been examined by Penny et al. [26], in order to minimize data analysis requirements in Wireless Sensor Network (WSN) systems, but they refer that more work is needed in order to develop these methods to be efficient. Also the sampling rate they use is very high (1600Hz) in order to evaluate it in a WSN system and it is unknown if the same computational approximations could be achieved with a much lower sampling rate of e.g. 200 Hz per sensing node.

B. Limitation and weaknesses of the existing structural fault detection methods

Literature [3, 5-7, 9, 11, 12, 15-18, 20, 22, 25-35] reveals that there are major drawbacks in the existing SHM methods. First of all, it is required a data history before the damage of the structure in order to be compared with the data after the damage. This is very important because usually the time of damage occurrence is unpredictable, so as to distinguish the data before and after the damage.

Literature does not define the exact deployment and the number of sensors in a structure. This issue is under research and in every structure a careful examination should take place to find the optimum sensor deployment, but even in that case there is no guarantee that rich data will be captured.

Another important constrain is that almost every known method is applied to linear structural models. In contrast, when structural damage occurs there is non-linear behavior, so there is possibility not to be able of recording the specific structural response.

Equally important is the issue concerning the difficulty to discriminate noise from data that reveal damage. The sensitivity of the sensors is an open challenge since the literature has not define yet specific minimum and maximum levels of data and noise respectively, or there is not a clear method to identify the valuable data in the noise when the level of signal is very low. Moreover, it is very difficult to discriminate statistical variation from low level damage SHM recordings.

Furthermore, the majority of SHM tests, methods and research is conducted in laboratories and models differ from real structures.

III. Description of the Proposed DSP Method to be Applied on SHM

Towards an adequate yet simple Digital Signal Processing method which will be able to satisfy most of the limitations and disadvantages of the existing methods, a new method is proposed.

This method attempts to improve the comparison of the previous (before damage) data with new (after damage) data without any prerequisite. It calculates only the current fundamental frequency spectrum dispersion and suggests that this distortion is different in case of damage and in case of health.

Also it reduces the complexity of the problem formulation. It is based on the simple physical principle of frequency dispersion and it requires minimum process power and interpretation.

The applied philosophy is that a simple equation comes closer to a physical law that correlates the stiffness with the fundamental frequency of a structure than a complex equation. The proposed method relies on the principle that stiffness of a structure is strongly related with the fundamental frequency of the specific structure [5-7, 36].

In this method we combine Fast Fourier Transform with Wavelet Transform in SHM recordings, in order to monitor real structures and extract data which may consist of valuable information.

The algorithm is applied in real structures investigate a realistic model.

The sensitivity is defined for each measurement at the minimum level (the level of environmental noise).

This algorithm is based on an effort to unify all the aforementioned methods, in order to propose a correlation between them and offer a parameter that reveals the excitation of a structure.

The main idea is that a system has very small limits of dispersion of its fundamental (natural) frequency when no damage has occurred, and this dispersion enlarges as the damage becomes higher. Figure 1 presents an example where the fundamental frequency of a structure changes with time denoting so changes of the stiffness of the structure. The dispersion of fundamental frequency gets higher as the mean value of the frequency gets lower and also the stiffness of the structure is reduced.

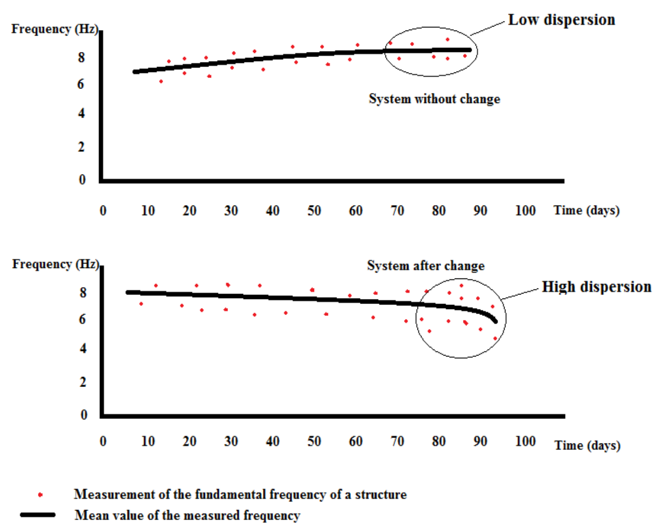

Fig.1 Low and high dispersion of fundamental frequency of a structure

The new algorithm is applied to the real SHM data recorded with the deployment of a wired network of accelerometers at the premises of the Technological Educational Institute of Crete (TEI of Crete), in city of Chania. The collected SHM data were analyzed by the proposed method and the results are discussed in detail, correlating and comparing these results with the methods that discussed above.

The proposed method is used to measure the stiffness of a structure and the loss of stiffness. It applies the principle that natural frequency is the most sensitive parameter to any change of a system, so if there is a change in modal parameters, e.g., in stiffness, in dynamic response of the structure, the first parameter that depicts the change is its fundamental frequency. Frequency is the result of response, so any change has influence in fundamental frequency. The proposed formulation has as follows:

$$\boldsymbol{\Pi} = 1 - \frac{f_{max} - f_{min}}{f_{mean}} \qquad (1)$$

Where $\boldsymbol{\Pi}$ is the new proposed index, f_{max} is the maximum fundamental frequency that appears in the spectrum, f_{mean} is the mean of fundamental frequency value of all the fundamental frequencies that have been measured (the whole variation of fundamental frequency) and f_{min} is the minimum frequency that appears in the spectrum.

The suggested method has a major advantage as concern the problem of historical data of SHM. In the literature, all the methods require SHM data of the structure before damage in order to compare them with the current data.

In equation (1) it is used the maximum and the minimum recorded fundamental frequency and not the conventional variance, because we are interested for the maximum difference of highest and lowest frequency (whenever it has occurred) and not the simple conventional variance of a specific measurement.

With this method, the knowledge of past (before damage) data is not necessary. If there is damage the $\boldsymbol{\Pi}$-index will have different value that if there is not damage due to the fact that in a healthy structure the frequency variation will be small. Furthermore, if there is already damage of the structure the $\boldsymbol{\Pi}$-index will have completely different value (lower than 1). As the damage increases the index will become lower, closer to zero.

IV. Units Application of the Π-index to SHM data

The new $\boldsymbol{\Pi}$-index is implemented in a wired SHM system deployed at an 18 years old 3 floor building and an adjacent 4 years old 3 floor building. At each building we deployed one accelerometer at the ground floor, one at the second floor and one at the highest floor (Fig.2).

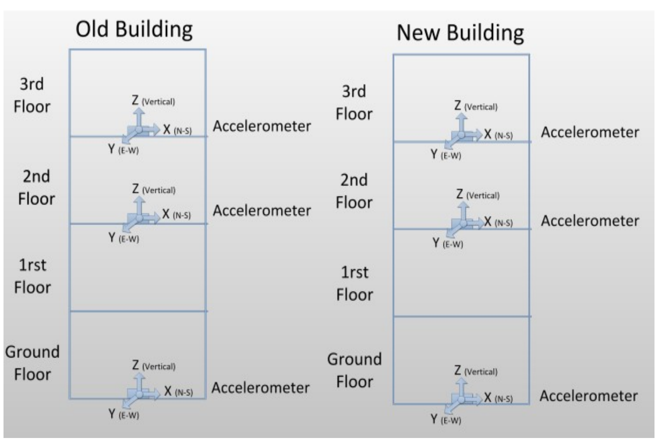

Fig.2 Schematic Deployment of the accelerometers in the buildings

The buildings are located in the city of Chania, Crete, Hellas a region characterized by high seismicity (see Fig. 3).

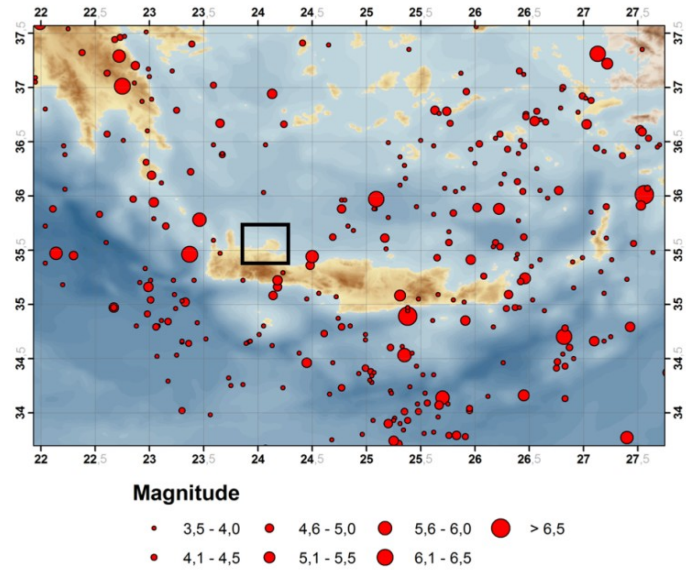

Fig.3 Seismicity of South Aegean in the period 2007-2010 recorded by the stations of the Seismological Network of Crete (MLWA>=3.5) and location of Technological Educational Institute of Crete in the city of Chania (35°31'9.30"N, 24° 2'34.35"E)

A. Contribution of the proposed index

- Very easy and fast analysis of the recording data.
- Low process requirements.
- No need for data knowledge before damage (no need for comparison with historical data).

B. Expression of the equation

We assume that if there is damage in a structure the differences between f_{max} and f_{mean} as well as between f_{mean} and f_{min} are bigger than the difference without damage. Thus, measuring the dispersion of fundamental frequency we could find the damage in the structure.

V. Recordings of Acceleration for Both Buildings

During the deployment of the wired SHM network in the two buildings of the TEI of Crete in Chania, PSDs (Power Spectral Densities) from accelerometer recordings have been investigated at various positions in order to identify where the fundamental frequencies are monitored more clearly from the accelerometers.

The experimental SHM set-up records acceleration of both buildings caused from natural hazards (seismic activity), for more than 3 months. The data are recorded and analyzed by applying FFT in order to present the frequency spectrum. Fundamental frequencies of both buildings are being monitored and the proposed $\boldsymbol{\Pi}$-index is calculated from SHM records. Then WT is being applied to the measurements in order to depict possible dispersion in time and frequency plane, of the fundamental frequency response of each building (Figs 4-6 & 7-10).

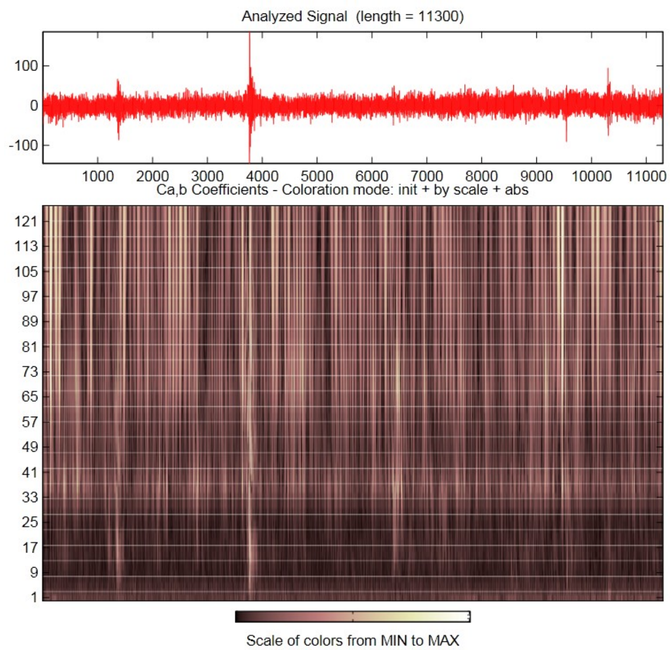

Fig.4 The 2012/11/23 02:08 UMT seismic event, recorded at 3rd floor of new building (3NB) accelerometer, North-South component (NS) 9F8E accelerometer , analyzed with Wavelet Transform , WV family db (level 2)

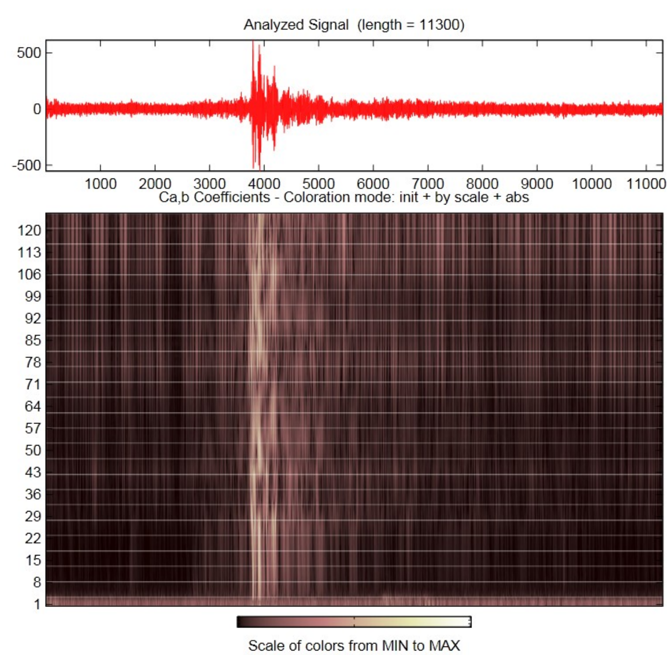

Fig.5 2012/12/05 06:54 UMT seismic event, recorded at 3rd floor new building (3NB) accelerometer, North-South component (NS) 9F8E accelerometer , analyzed with Wavelet Transform , WV family db (level 2)

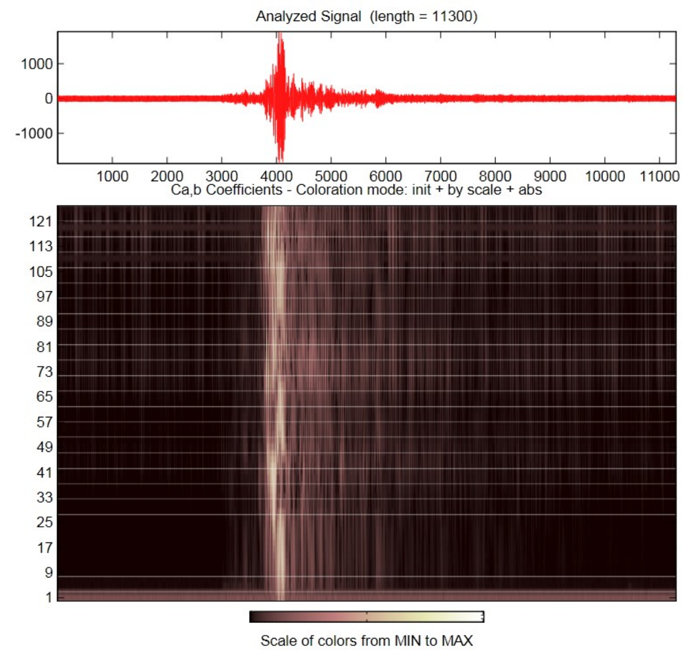

Fig.6 2013/01/05 02:04 UMT seismic event, recorded at 3rd floor new building (3NB) accelerometer, North-South component (NS) 9F8E accelerometer , analyzed with Wavelet Transform , WV family db (level 2)

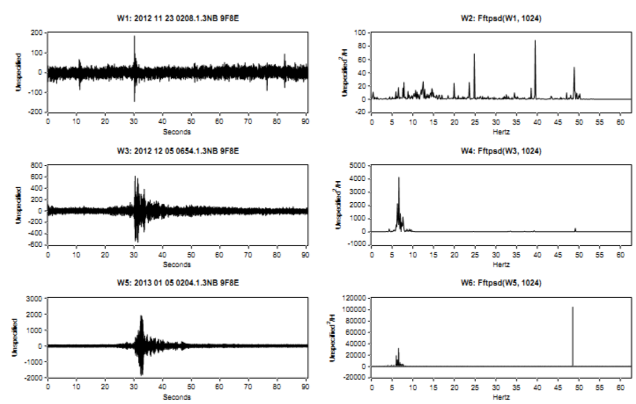

Fig.7 FFT based PSDs for the previous events (Figs 3,4 &5)

For the case of Fig. 4, the signal is very weak and therefore many frequencies are observed (the fundamental frequency of the new building can not be revealed). In Fig. 5 the seismological recording has very clear spectrum and the fundamental frequency of the new building is 6.6Hz. Fig. 6 depicts fundamental frequency 6.5Hz. All these are also depicted in Fig. 7.

Thus, there is a frequency dispersion of 0.1 Hz in fundamental frequency. Consequently, $\boldsymbol{\Pi}$-index of the new building is calculated:

$$\boldsymbol{\Pi} = 1 - \frac{f_{max} - f_{min}}{f_{mean}} = 1 - \frac{6.6 - 6.5}{6.55} = 1 - 0.015 = 0.985$$

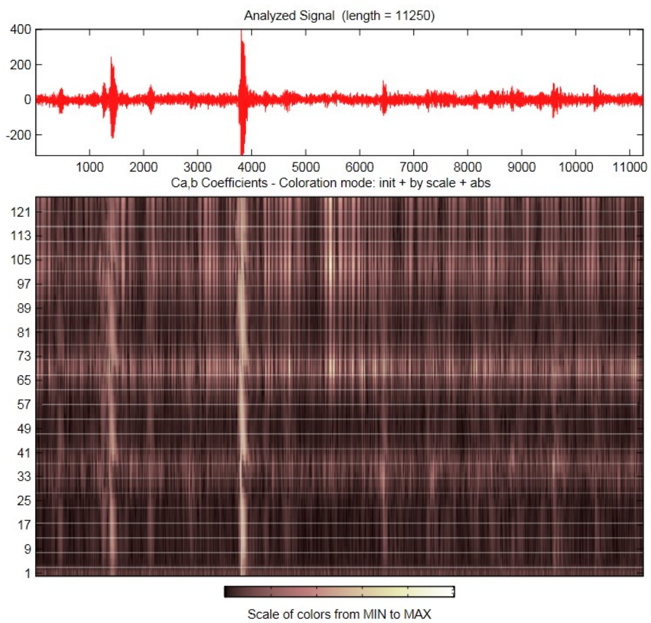

Fig.8 2012/11/23 02:08 UMT seismic event, recorded at 3rd floor old building (3OB) accelerometer, North-South component (NS) A392 accelerometer , analyzed with Wavelet Transform , WV family db (level 2)

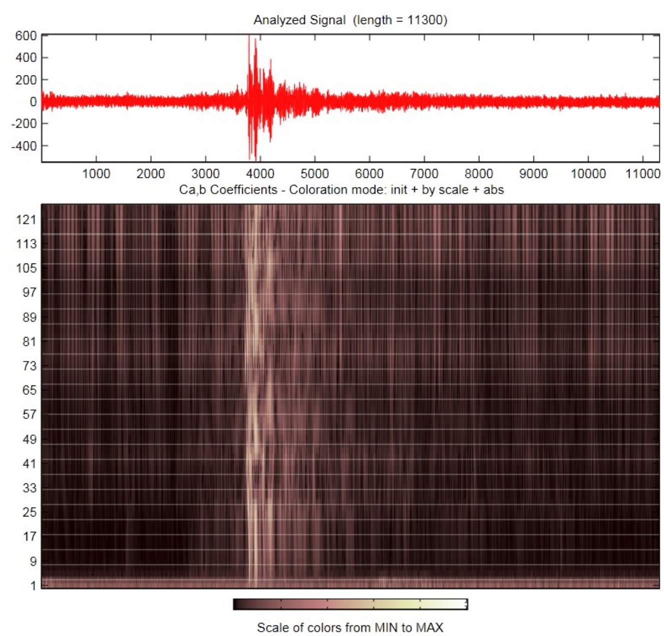

Fig.9 2012/12/05 06:54 UMT seismic event, recorded at 3rd floor old building (3OB) accelerometer, North-South component (NS) A392 accelerometer , analyzed with Wavelet Transform , WV family db (level 2)

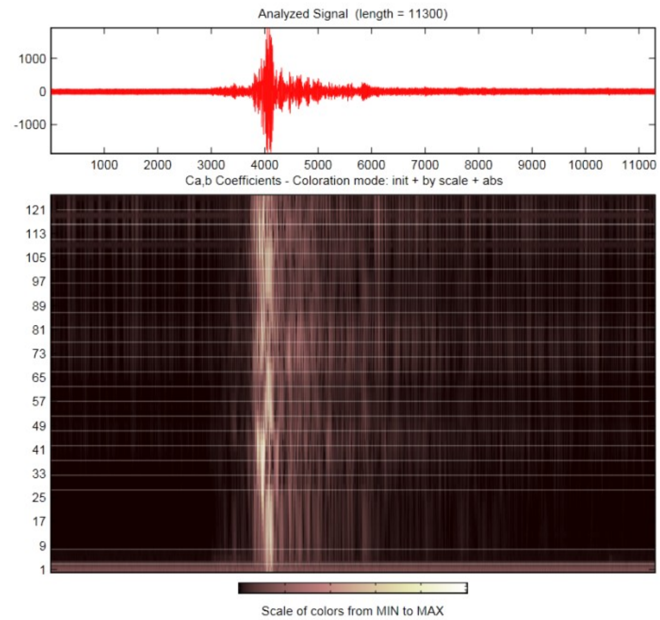

Fig.10 2013/01/05 02:04 UMT seismic event, recorded at 3rd floor old building (3OB) accelerometer, North-South component (NS) A392 accelerometer , analyzed with Wavelet Transform , WV family db (level 2)

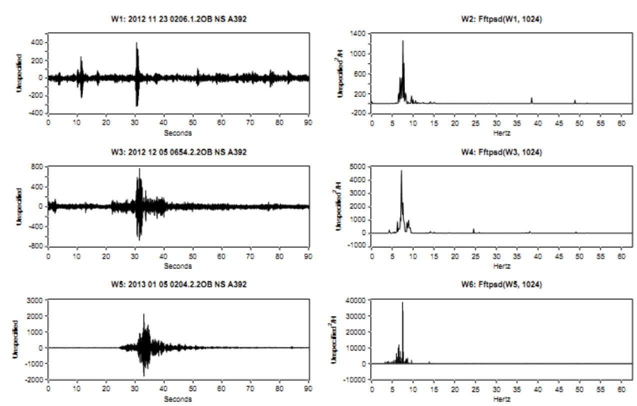

Fig.11 FFT based PSD for the previous events (Figs 7,8 &9)

The fundamental frequency of the old building can be revealed from Figs 8, 9, 10 and 11. The accelerometer recordings have very clear spectrum and the fundamental frequency is fluctuating from 7.25Hz to 7.55Hz with a mean value (from a number of recordings) at 7.48Hz.

Thus there is a frequency dispersion of 0.3Hz in fundamental frequency.

Consequently, $\boldsymbol{\Pi}$-index of the old building is calculated:

$$\boldsymbol{\Pi} = 1 - \frac{f_{max} - f_{min}}{f_{mean}} = 1 - \frac{7.55 - 7.25}{7.48} = 1 - 0.0401 = 0.9599$$

This value is lower than the value from the new building. It is expected because the old building it is anticipated to have lower structural stiffness and higher fundamental frequency dispersion.

We study also the resonance frequencies which appear in the vertical and in the East-West components for both buildings in the upper seismic events.

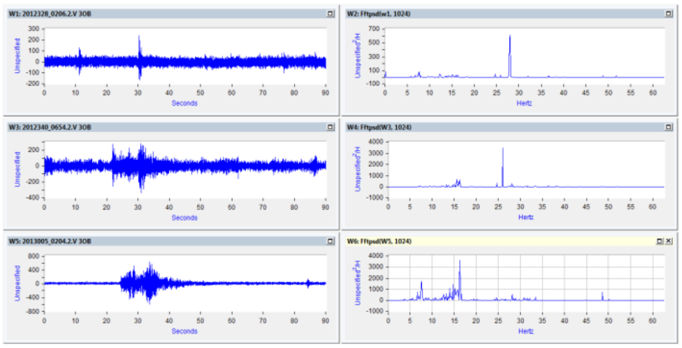

Fig.12 FFT based PSDs for the previous events (up 2012/11/23 02:08 UMT, middle 2012/12/05 06:54 UMT and lower 2013/01/05 02:04 UMT) for the old building (Vertical component)

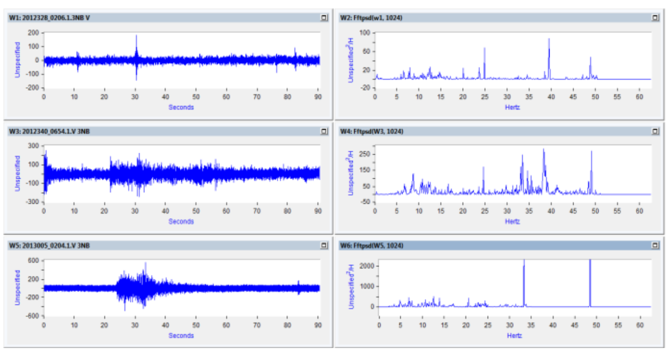

Fig.13 FFT based PSDs for the previous events (up 2012/11/23 02:08 UMT, middle 2012/12/05 06:54 UMT and lower 2013/01/05 02:04 UMT) for the new building (Vertical component)

The seismic acceleration of the earthquake events, effect very low in the vertical components (for both buildings), although the same earthquakes have much higher magnitude in the two horizontal components. This results the resonance frequency of the structure to be unable to reveal. The peaks that present in the FFT spectrums are noises.

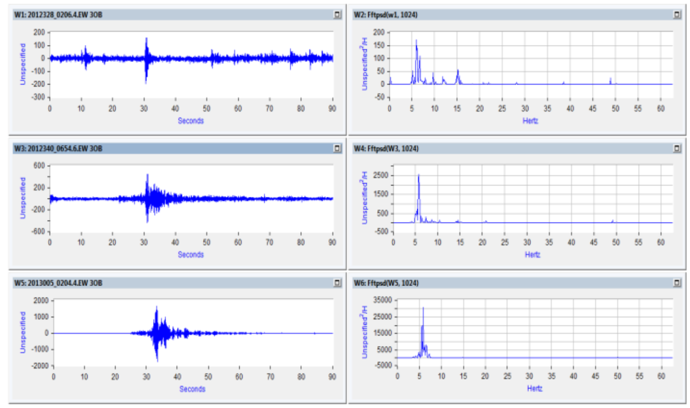

Fig.14 FFT based PSDs for the previous events (up 2012/11/23 02:08 UMT, middle 2012/12/05 06:54 UMT and lower 2013/01/05 02:04 UMT) for the old building (East-West component)

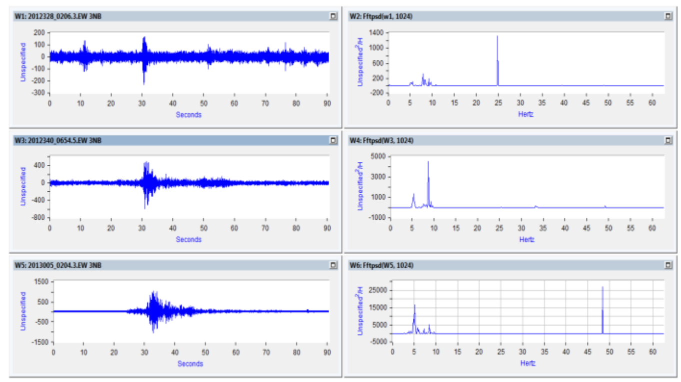

Fig.15 FFT based PSDs for the previous events (up 2012/11/23 02:08 UMT, middle 2012/12/05 06:54 UMT and lower 2013/01/05 02:04 UMT) for the new building (East-West component)

In this part of the work we are going to apply Short Time Fourier Transform (STFT) in our recordings, in order to define and reveal the frequencies that appear for each earthquake with STFT and distinguish the differences from the Wavelet transform that applied above.

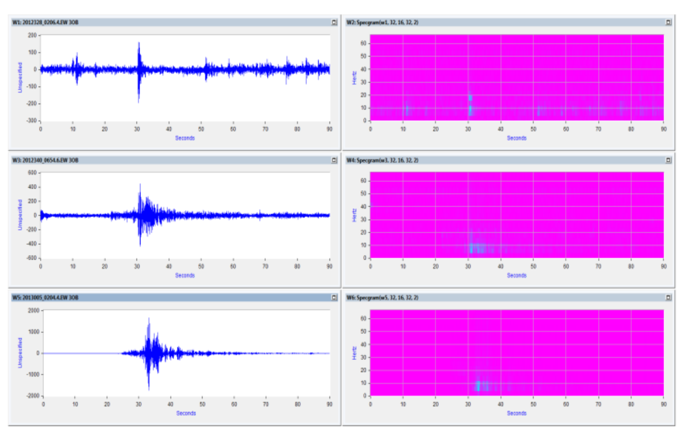

Fig.16 Spectrogram for the previous events (up 2012/11/23 02:08 UMT, middle 2012/12/05 06:54 UMT and lower 2013/01/05 02:04 UMT) for the old building (East-West component)

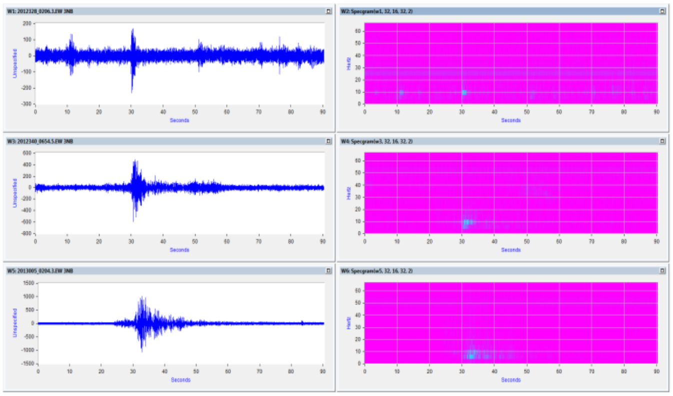

Fig.17 Spectrogram for the previous events (up 2012/11/23 02:08 UMT, middle 2012/12/05 06:54 UMT and lower 2013/01/05 02:04 UMT) for the new building (East-West component)

STFT presents the frequency spectrum of each recording at the specific time that occurs, but the maximum resolution is limited by the length of the specific window that is used for STFT. In figures 16 and 17 darker points reveal larger amplitude coefficients. By wavelet transform we are able to see the coefficients of the specific wavelet that is used (in our study db2) in many scales (from the maximum frequency (125 Hz) until the minimum desired frequency) and study what signals are contained in our recordings, and when they occur, in great detail. In the figures 4-6 & 8-10 with wavelet transform, we do not see windowed Fourier transform of the signal (like STFT), but the coefficients that are produced by the wavelet transform of the signal with the specific wavelet. The brighter levels indicate larger amplitude of the corresponding wavelet packet coefficient [37].

The analysis of both methods (wavelet and STFT) reveal that there is higher detail with the wavelet method, such the disturbances of the signals and the discontinuities are much more obvious with WT and also the resonance frequencies and the time that every frequency occurs, can be revealed with higher accuracy.

From the above measurements (fig. 12-17) we observe that at the east-west component the resonance frequency for the new building is:

$$\boldsymbol{\Pi} = 1 - \frac{f_{max} - f_{min}}{f_{mean}} = 1 - \frac{5.25 - 5.20}{5.225} = 1 - 0.0095 = 0.9904$$

And also for the old building the resonance frequency for the old building is:

$$\boldsymbol{\Pi} = 1 - \frac{f_{max} - f_{min}}{f_{mean}} = 1 - \frac{5.85 - 5.55}{5.76} = 1 - 0.052 = 0.948$$

We observe that the range of the $\boldsymbol{\Pi}$ index, in the east-west component, is very close to the range of the North-South component for the old and the new building respectively. This indicates that the frequency dispersion of the fundamental frequency is almost the same for the two horizontals components in both buildings.

VI. Discussion

On the previous recordings, the fundamental frequency of the buildings of the premises of TEI of Crete in Chania is recorded in detail and determined accurately. The limits where frequency fluctuates, shows us the frequency dispersion of the fundamental frequency for each building and was defined by the maximum and the minimum recorded frequency. The old building (18 years old) has higher frequency dispersion than the new building (4 years old) and this indicates that, although the buildings have the same structural characteristics probably, the old one has suffered more damage than the new one mainly due to seismic activity all these years.

VII. Conclusions

Conclusively, the SHM data presented in this work demonstrate examples of frequency dispersion.

The main objective was to propose a new index $\boldsymbol{\Pi}$ “Frequency dispersion” as a parameter sensitive to the health of a structure.

The damage of a structure is defined as changes which are taking place in a system and affect its present and/or future efficiency.

The study and monitoring of structural health always requires the comparison of two states, before and after damage. This work proposed an algorithm that overpasses this prerequisite.

The main idea is that when one or more parameters change in a system, the fundamental frequency, which characterizes the system’s structural behavior, depicts different frequency dispersion than before.

The proposed $\boldsymbol{\Pi}$ –index is a simple equation that comes closer to a physical law that correlates the stiffness with the fundamental frequency of a structure. Furthermore, through its definition, the knowledge of past (before damage) data is not necessary.

This method is relying in the simple, basic principle of dispersion of a value. This dispersion should be in specific limits and when these limits get higher then there is change in the whole system.

As a real case study, the proposed algorithm was implemented to the data collected from a wired SHM system deployed in at 18 years old, 3-floor building and an adjacent 4 years old, 3-floor building at the premises of the Technological Educational Institute of Crete, in city of Chania.

Acknowledgment

This work was supported in part by the Archimedes III Program of the Ministry of Education of Greece, through the Operational Program "Educational and Lifelong Learning", in the framework of the project entitled «Interdisciplinary Multi-Scale Research of Earthquake Physics and Seismotectonics at the front of the Hellenic Arc (IMPACT-ARC)» and is co-financed by the European Union (European Social Fund) and Greek National Fund.

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