

Structural health monitoring of COMSOL designed micro cantilever beam using wavelet transform for biosensing medical applications

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Abstract: Structural health monitoring is a process of identifying the presence of damages in the structures and to evaluate the damage condition. Structural health monitoring based on dynamic characteristics such as frequency, displacement and stress are used as common tool to determine the damage exists in the structure. Here a new method was proposed to detect the cracks present in the micro cantilever beams using wavelet transform. Wavelet analysis is one among the efficient tool for SHM applications due to its ability of multi scale analysis of transient data. Wavelet transform has overcome many limitations of widely used Fourier transform and gained popularity in SHM systems. Here the changes in wavelet coefficients were used to detect the cracks location in the surface of the cantilever beam with multiple cracks. The micro cantilever beam is modeled using COMSOL multiphysics software. The obtained results show that the wavelet coefficients are directly influenced by stress over the cracked portion of the structure and by which the location of the cracks can be exactly located.

Keywords: Wavelet Analysis, SHM, Crack Detection, Cantilever Beam, MEMS, COMSOL.

1. Introduction

Structural health monitoring (SHM) and damage detection in microstructures had become a needed technology to study. Detecting and locating such damages over the structure of micro device on right time is very essential to avoid early device failures. Detecting the damages by its dynamic characteristics like deflection or stress experienced over the device is found to be an efficient method [1]. Even the slight damage in microstructures will reflect in the device overall performance to a greater extend unlike normal macrostructures. In recent SHM systems many advanced technologies and intelligent method such as digital filters technology, artificial neural network and wavelet transform (WT) were applied for damage detection. In wavelet transform

analysis, the wavelet coefficients were used to describe the changes in the obtained output signal with sharp spikes or discontinuity [2][3][4].

Wavelet transforms which was introduced in early 1980's by J.Morlet and A.Grossmann was very much concentrated over theoretical mathematics than its applications [5]. Later Daubachies and Mallet changed this by defining the wavelets for various applications like time frequency spectral analysis, digital signal processing, data compression and image processing. Fourier analysis was the important tool in signal processing till the WT was modified. The Fourier transform (FT) decomposes the function in a range of low to high frequency components, which have a narrow support in one domain. But the wavelet has basis functions on both domains. Fourier signal does not contains any local data and found to be in appropriate in analyzing the time varying signals [6][7]. This deficiencies experienced in Fourier analysis made the researches to find the alternative to overcome this issues. WT is found to be the direct alternative to FT in time-frequency analysis of discrete signals [8]. Since WT has its origin in mathematical theory, its application and implementation of very simpler as the theory suggests.

In this present work, we utilize the wavelet coefficients to analyze the output signal from a micro structured cantilever beam to locate any damages or cracks present. The wavelet coefficients will reflect with peaks when any changes or discontinuities occur in data. By the use of such ridges and peaks in wavelet analysis, we could exactly locate the cracks and damages present in the micro device. Dynamic characteristics of the device will reflect with respect to the damage or cracks over the surface. Here we had compared devices with various dissimilarities in the device surface. The device with structural damages is compared with healthy device and the presence of location is identified by use of wavelet transform analysis [9][10][11].

2. Wavelet Theory

According to Fourier theory, a signal can be expressed as the sum of series of sine and cosine. This sum is also called as Fourier expansion as shown in equation (1). The set back of Fourier transform is that only has frequency resolution and no time resolution. To overcome this, the wavelet theory is proposed.

$$F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t} dt$$

$$= \int_{-\infty}^{\infty} f(t)(\cos\omega t - j \sin\omega t)dt \quad \text{-----1}$$

Mathematically, wavelet can be defined as a function with zero average. The basic idea of the wavelet transform is to represent any function as a superposition of a set of wavelets or basis functions [16]. Because these functions are small waves located in different times, the wavelet transform can provide information about the time and frequency domains.

$$\int_{-\infty}^{\infty} \psi(t)dt = 0 \quad \text{-----2}$$

2.1 Continuous wavelet transforms (CWT)

Similar to equation (1) the continuous wavelet transform is defined as

$$\gamma(s, \tau) = \int_{-\infty}^{\infty} f(t)\psi_{s,\tau}^*(t)dt \quad \text{-----3}$$

Where * denotes complex conjugation. The variable s and τ are the new dimensions, i.e. scale and translation, after the wavelet transform the equation (3) shows that a function f(t) is decomposed into a set of basic functions $\psi_{s,\tau}(t)$ which is called wavelets. And the wavelets are generated from the mother wavelet by scaling and translation:

$$\psi_{s,\tau}(t) = \frac{1}{\sqrt{s}}\psi\left(\frac{t-\tau}{s}\right) \quad \text{-----4}$$

Where 's' is a scale factor that reflects the scale i.e., width of a particular basis function. τ is a translation factor that specifies the translated position along the t axis and the factor $\frac{1}{\sqrt{s}}$ is for energy normalization across the different scales.

2.2 Discrete wavelet transforms (DWT)

The disadvantage of the continuous wavelet transform lies in its computational complexity and redundancy. In order to solve the problems, the discrete wavelet transform is introduced. Unlike CWT, the DWT decomposes the signal into mutually orthogonal sets of wavelets. The discrete wavelet is defines as

$$\psi_{j,k}(t) = \frac{1}{\sqrt{s_0^j}}\psi\left(\frac{t-k\tau_0 s_0^j}{s_0^j}\right) \quad \text{-----5}$$

Where j and k are integers, $s_0 > 1$ is a fixed dilation step and translation factor τ_0 depends on the dilation step. The scaling and wavelet function of DWT are defines as,

$$\varphi(2^j t) = \sum_{i=1}^k h_{j+1}(k) \varphi(2^{j+1} t - k) \quad \text{-----6}$$

$$\psi(2^j t) = \sum_{i=1}^k g_{j+1}(k) \varphi(2^{j+1} t - k) \quad \text{-----7}$$

And then a signal $f(t)$ can be written as:

$$f(t) = \sum_{i=1}^k \lambda_{j-1}(k) \varphi(2^{j-1} t - k) + \sum_{i=1}^k \lambda_{j-1}(k) \psi(2^{j-1} t - k) \quad \text{-----8}$$

A time series $X(t)=[x_1, x_2, x_3, \dots, x_n]$ can be decomposed by cascade algorithms as follows,

$$\begin{aligned} x(t) &= A_1(t) + D_1(t) \\ &= A_2(t) + D_2(t) + D_1(t) \\ &= A_3(t) + D_3(t) + D_2(t) + D_1(t) \\ &= A_n(t) + D_n(t) + D_{n-1}(t) + \dots + D_1(t) \end{aligned}$$

Where $D_n(t)$ and $A_n(t)$ are detail and approximation coefficients at level 'n' respectively. Figure.1 illustrates the corresponding wavelet decomposition tree.

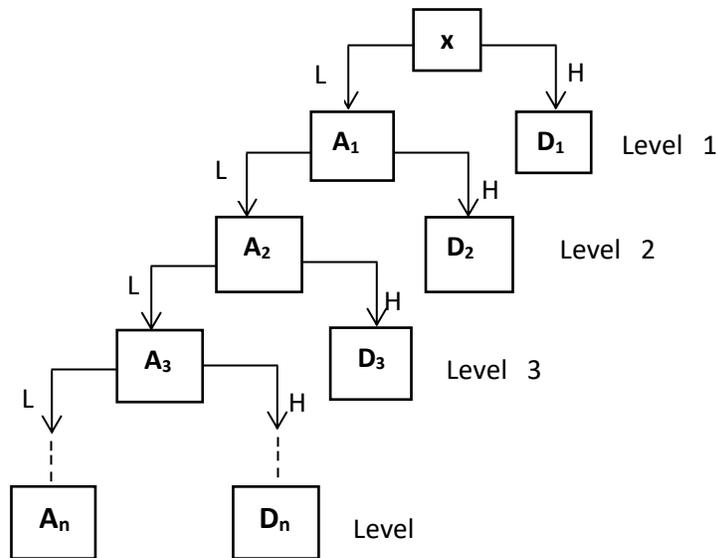


Figure.1 Wavelet Decomposition Tree

The Haar Wavelet is defined as follows:

$$\psi(x) = \begin{cases} 1 & 0 \leq t \leq \frac{1}{2}, \\ -1 & \frac{1}{2} \leq t < 1, \\ 0 & \text{otherwise} \end{cases}$$

Further $\int_0^1 |\psi(x)|^2 dx = 1$ and the scaling function for Haar wavelet is given by,

$$\phi(x) = \begin{cases} 1 & \text{if } x \in [0,1] \\ 0 & \text{if } x \notin [0,1] \end{cases}$$

(i.e) $\phi(x)$ is the characteristic function of the closed interval $[0,1]$.

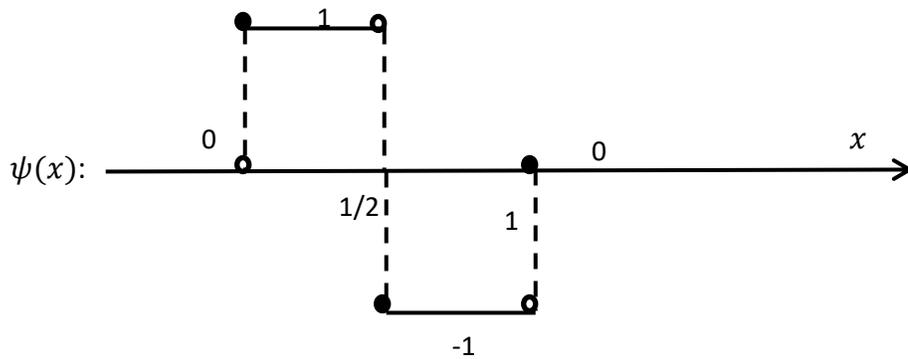


Figure.2 Haar Wavelet

Daubechies wavelet(dbN)

Since Haar wavelet is the simplest and oldest wavelet transform; it was improved by Daubechies in 1992. He developed the frequency - domain characteristics of the Haar wavelet. However, we do not have a specific formula for this method of wavelet transform. So we tend to use the square gain function of their scaling filter, the square gain function was defined as,

$$\Gamma(f) = 2 \cos^N(\pi f) \sum_{i=0}^{\frac{L}{2}-1} \binom{\frac{N}{2}-1+l}{l} \sin^{2L}(\pi f) \quad \text{-----9}$$

Where the length N of the filter is a positive even integer. The name of the Daubechies Family wavelets are written dbN, Where N is the order. Here for our study we had analyzed the signal

along the axis of the beam using DWT. We analyzed the both Haar and Daubacheius wavelets for locating the cracks present in the micro cantilever beam.

3. Micro Cantilever Beam

Cantilever beam is a mechanical structure fixed at one end and free at the other end. When a cantilever is subjected to a load, it will bend to extend due to the load and stress will be generated over the structure due to its deflection. Micro cantilever beam whose dimension will be in micrometer scale will results with large displacement for small change in mass, force or stress. Micro cantilevers are primarily used in sensors, switches, actuators and transducers [12]. Micro cantilever based sensor is one of the most commonly used mechanical sensor. Cantilever devices are used as transducer which converts mechanical behavior of cantilever into measurable signals. Physical changes occurred in the devices due to external disturbances or environmental changes effects the mechanical behavior. Micro cantilever based devices found its application in gas, temperature, pressure and biological sensors. Its reduced micro scale dimension will make them more sensitive, cost effective and faster. It can be implanted over any surface due to its reduced dimension and compatibility. Bulk micromachining and surface micromachining are the most efficient fabrication techniques in fabricating such micro devices. The materials such as silicon, gold and platinum are widely used for fabrication due to its selectivity, sensitivity and ease of processing technology [13].

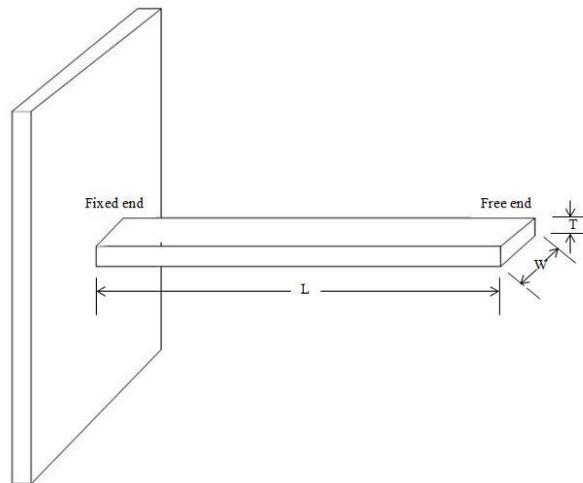


Figure.3 Basic Cantilever Beam Structure

The basic structure of the micro cantilever beam is shown in the Figure.3, where L represents the length of the beam, W is the beam width and T is the thickness of the beam. Bending or deflection caused in the beam can produce differential stress over the surface. These devices are

one among the efficient tool for sensing application due to its intrinsic flexibility. The sensing action is based on deflection of the beam and the stress developed due to external force. Since the device is sensitive for very small input changes it is necessary to monitor the device health to get efficient output [14][15]. Even a small damage or crack present in the device structure due to fabrication process or environmental conditions will reflect in the output to a greater extent. In this work we aim to identify the presence of cracks present in the device structure by analyzing the output signal of the measured device compared to the healthy cantilever beam with respect to the stress and total displacement[17][18]. Figure.4 shows the SEM image of cracks present in the micro cantilever structure which was reported earlier.

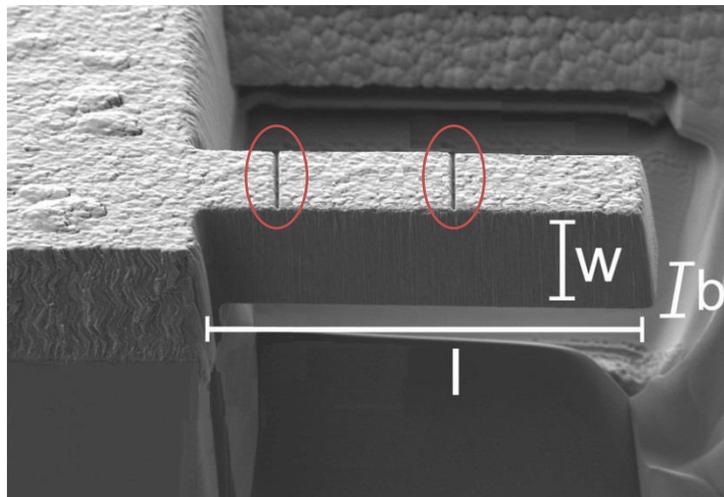


Figure.4 SEM image of representative Micro Cantilever Beam with cracks

4. Modeling of Micro Cantilever Beam structure

In our work, the structure of proposed micro cantilever is designed using COMSOL multiphysics5.4 simulation software. Computer simulation is very essential in developing new products and for optimization of particular design. COMSOL is one which helps to develop and determine the accuracy of the model with real world precision. The model can be tested over various geometrical characteristic and physical parameters. Defining the geometries, material property and physics of the model can be encompassed with step by step modeling workflow. COMSOL multiphysics5.4 brings enhanced modeling features for modeling thin layered structure. Any combination of add on modules for various engineering applications can be simulated using this tool.

In this proposed study, we had chosen poly crystalline silicon as device material due to its unique properties in fabricating micro structured devices. Material properties of Poisson ratio - 0.22, Density -2320kg/m³ and young's modulus-160Gpa is chosen. Next the device parameters of length (L) 150μm, width (W) 20μm and thickness (T) 2μm were fixed. The force (P) applied over the entire beam is 3.5x10⁻⁶N.

For the above mentioned, material property and device dimensions, we calculate the deflection of the device theoretically using the equation.10,

$$\delta = \frac{PL^3}{24EI} \frac{x^2}{L^2} \left(6 - 4\frac{x}{L} + \frac{x^2}{L^2}\right) \quad \text{-----10}$$

Where, x is the specific point the deflection to be calculated. We consider x=L for calculating the maximum deflection of the cantilever beam.

$$\delta_{max} = \frac{PL^3}{8EI} \quad \text{-----11}$$

Where, E is the young modulus of the material, I is the moment of inertia, P the force applied and L is the beam length , W-width ,T-thickness. Moment of inertia is given as equation.12,

$$I = \frac{1}{12} W \cdot T^3 \quad \text{-----12}$$

From the above equations, we calculated the theoretical value of maximum deflection to be $\delta_{max} = 0.687\mu\text{m}$.

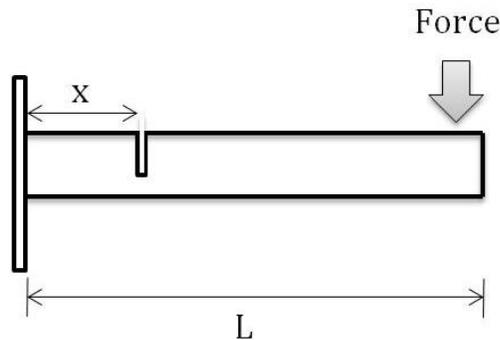


Figure.5 Schematic Cantilever Beam with single crack

For the purpose of locating cracks present in the device surface, we compared three devices with different cracks which were intentionally made over the device structure. The constant crack

dimensions of length $L=0.5\mu\text{m}$, width $W=10\mu\text{m}$ were made over all the three devices. Table.1 gives the details of cracks present in the respective devices.

Sl.No	Device	No. of Cracks Present	Location of the cracks in x axis
1	D	Nil	Reference Healthy Beam
2	D1	1	$30\mu\text{m}$
3	D2	2	$30\mu\text{m}$ & $60\mu\text{m}$
4	D3	3	$30\mu\text{m}$, $60\mu\text{m}$ & $100\mu\text{m}$

Table.1 Device details with crack locations

5. Simulation Result and Discussions

5.1 Deflection Analysis

A force applied across the beam's surface will cause it to deflect in all directions relative to the applied force. Here, we used a constant force of $3.5 \times 10^{-6}\text{N}$ in our investigation. For the purpose of comparing the device features, the force is maintained constant throughout all of our structures. The micro cantilever beam D, which is thought to be in good condition, exhibits a maximum deflection of $0.69\mu\text{m}$ for the force shown above. This device's maximum deflection is nearly identical to the predicted theoretical value. The device D1, which has a single crack, has a total displacement of $0.77\mu\text{m}$. The surface deflects more when a crack occurs than when the structure is in good condition.

With a total displacement of $0.80\mu\text{m}$, Device D2, which has two cracks, deflects more than the two constructions mentioned previously. Device D3, which has three cracks, finally displays a total displacement of $0.81\mu\text{m}$. The total displacement of the gadget is affected by the quantity of cracks present in its structure. In relation to the surface cracks, the beam's deflection rises. The device with the most cracks will deflect more than other device constructions, according to the research above. The graphic representation of the total displacement computed using COMSOL for the devices indicated above is displayed in Figure 4. A device is shown in Figure 6(a) as being healthy, a device with one crack in Figure 6(b), a device with two cracks in Figure 6(c), and a device with three cracks in Figure 6(d).

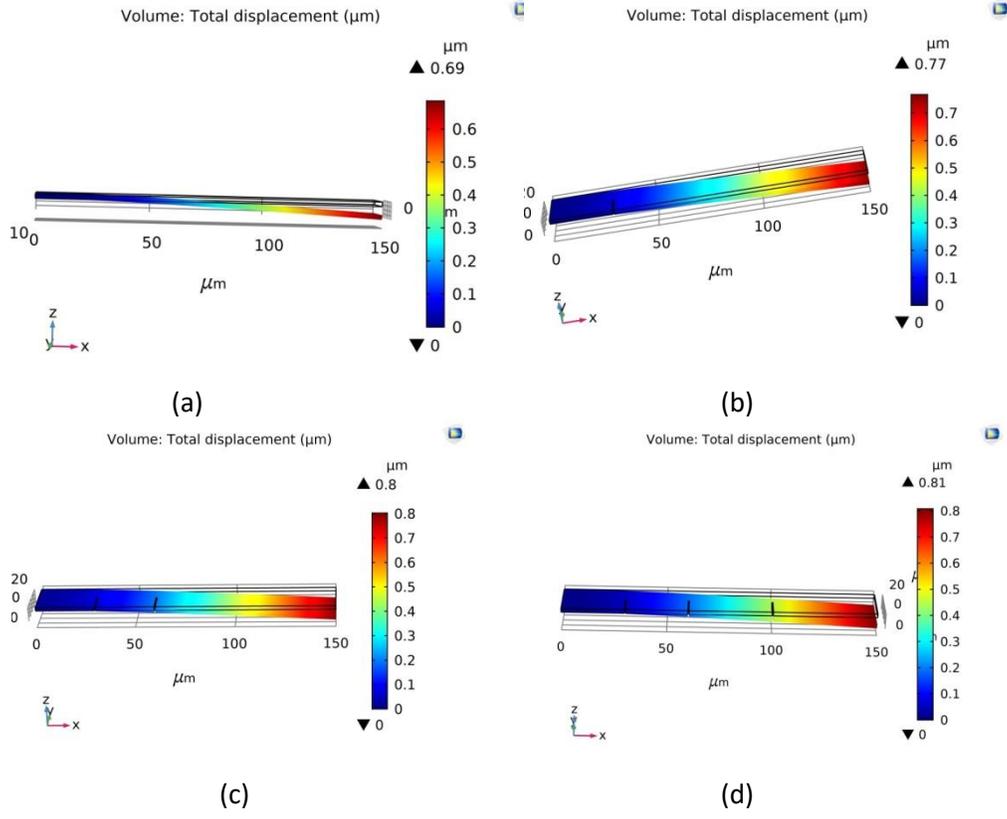


Figure.6 Total Displacement of devices by COMSOL analysis

The deformation of the beam structure for the three types is depicted in Figure 7.7 in terms of total displacement.

Since the deflection of devices D3 and D4 depends on the size and location of cracks, the differences in deflection are negligible. However, a broken beam with a healthy structure exhibits noticeable displacement.

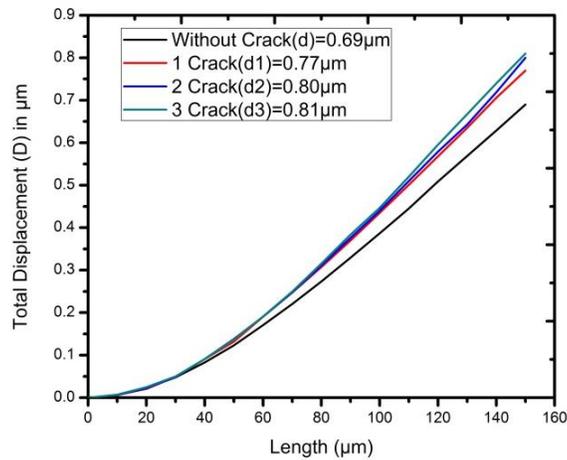


Figure.7 Displacement comparison of the devices

5.2 Stress Analysis

A cantilever beam will deflect as it is loaded, which will cause stress to build up as the force is applied throughout the entire structure. Typically, there will be the most stress.

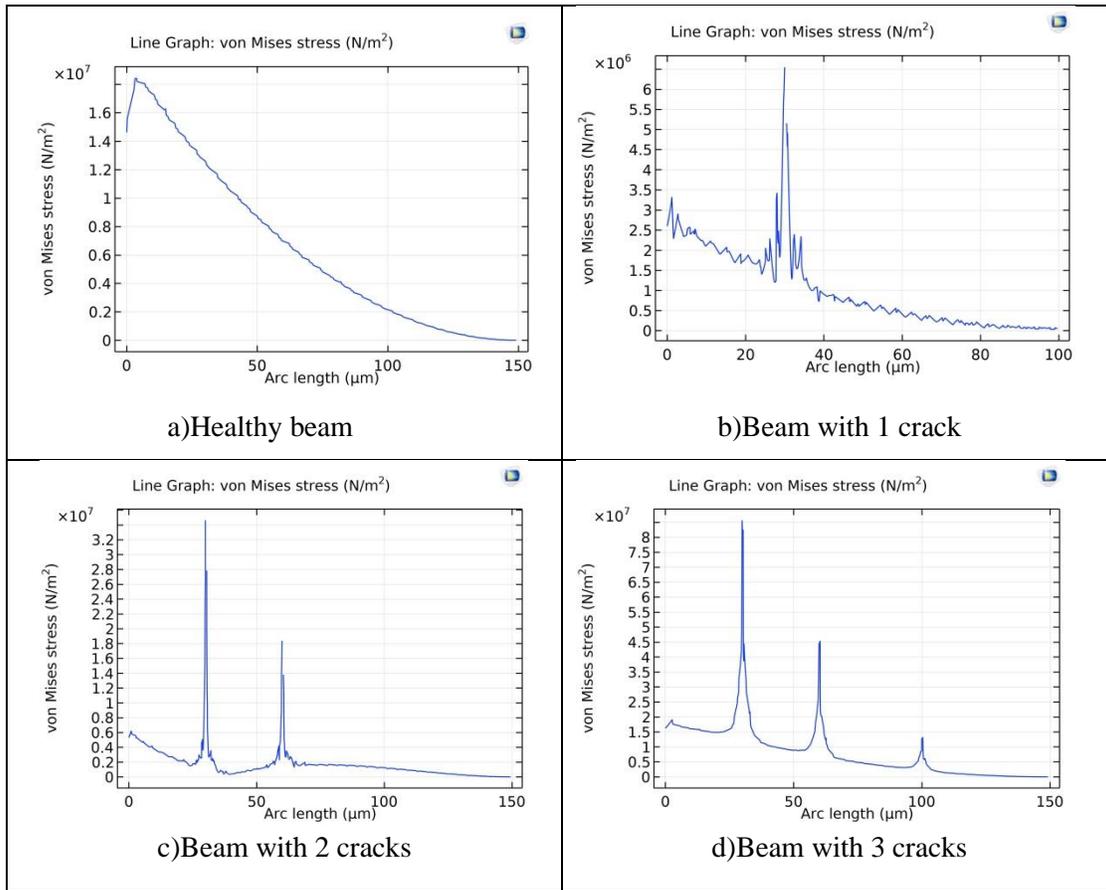


Figure.8 1D plot of stress over the devices

close to the fixed end since the weight will be concentrated there and progressively lessen as it moves toward the free end. However, the site of cracking in a structure will experience the highest level of stress. A one-dimensional picture of the stress over the device structure is shown in Figure 8. It makes the peak stress values over the device's fractured zone more evident. The cracked area of the device construction with the highest stress is shown in Figure 9. This is a graphical representation of stress. The crack close to the fixed end is determined to have the most stress.

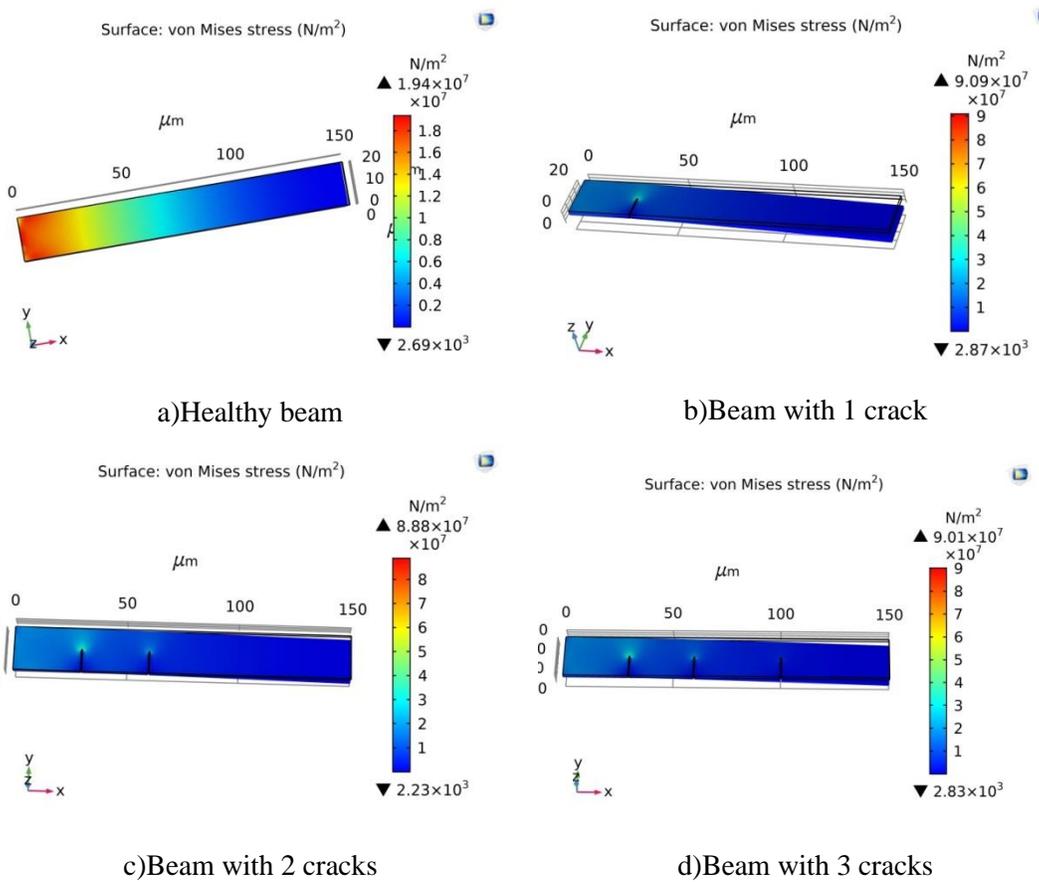


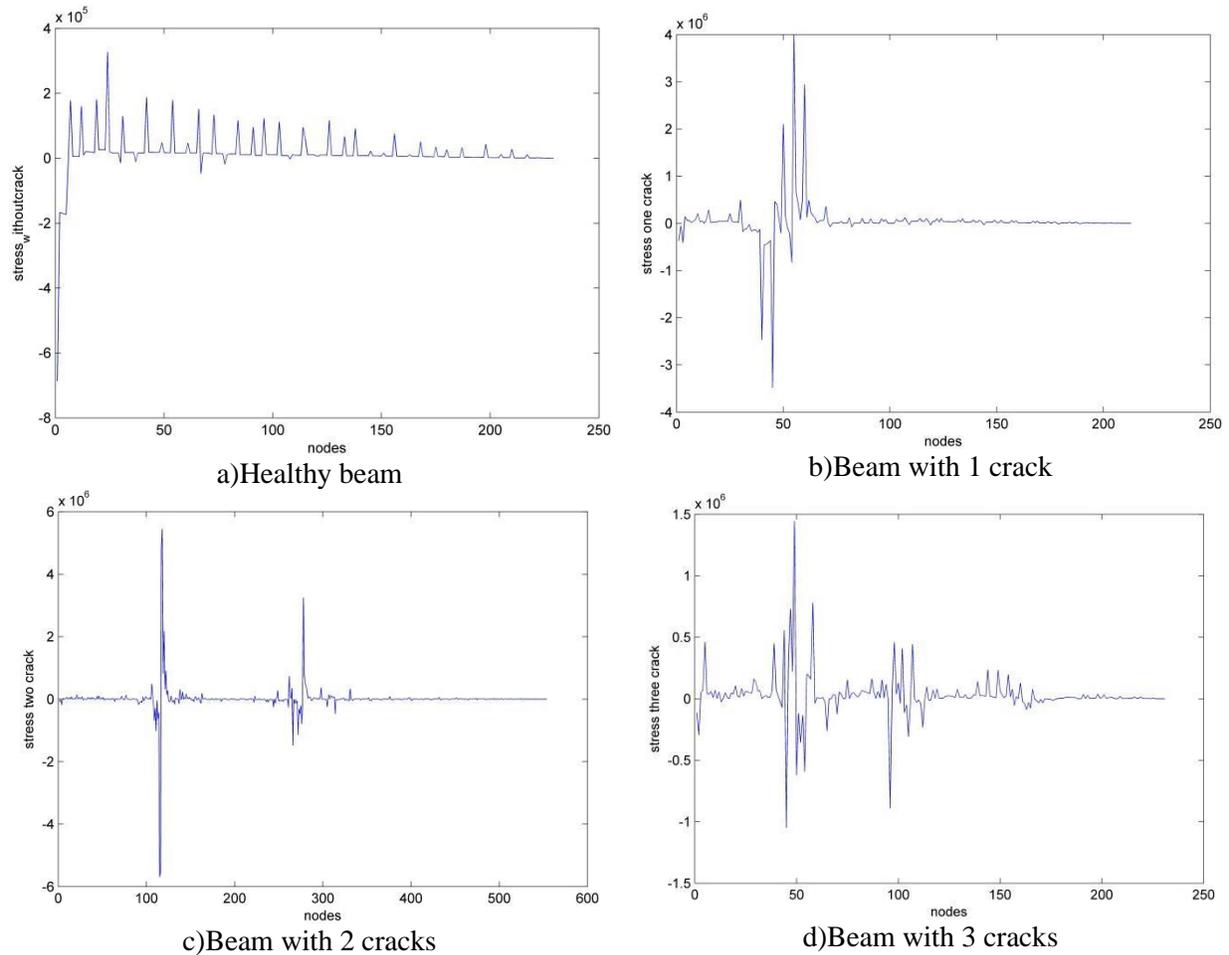
Figure.9 Pictorial representation of stress over devices

5.3 Analysis using Wavelet Transforms

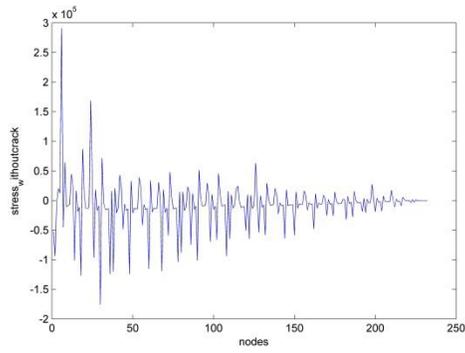
Wavelet coefficient analysis is used to examine the outcomes of the COMSOL simulation utilizing different mother wavelets, such as Haar and Daubechies. Choosing effective wavelet functions is typically accomplished through trial and error. Symmetric wavelets were chosen for use in applications such as fracture identification. The wavelet coefficients were found to exhibit peaks and ridges resulting from signal discontinuity. The wavelet coefficients for each device, derived from Haar mother wavelets, are shown in Figure 10. Where the crack is located on the beam's axis, the wavelet coefficient displays peaks.

The other devices display the peaks at the precise sites where the cracks were modeled, whereas the healthy beam displays the stress close to the fixed end. Compared to other fractures, the tension across the crack near the fixed end exhibits largest peaks.

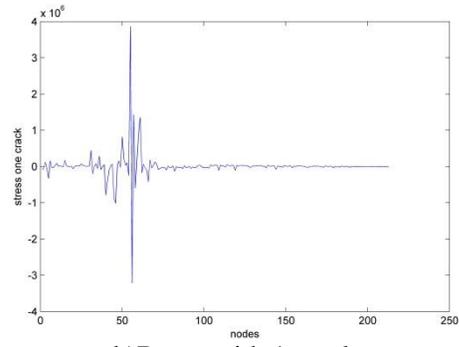
Figure.10 Wavelet coefficient of Haar wavelet



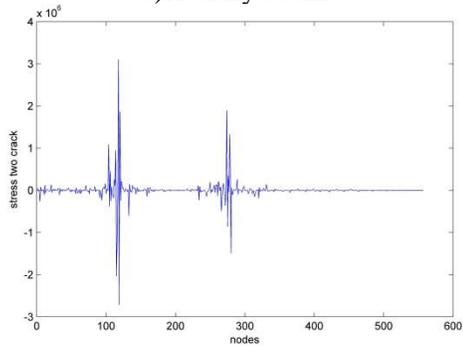
Daubechies wavelets have been shown to be effective in this domain and have been found to perform well in such applications. The polynomials Daubechies db4 and db8 encoding have two and four coefficients in each case. The phenomena of shift invariance and scale leaking, which result from discrete shifting during the transform's application, affect the signals' capacity to be encoded. The differences in wavelet coefficients employing Daubechies mother wavelets of db4 and db8, respectively, are shown in Figures 11 and 12. The Daubechies wavelet coefficients exhibit a greater degree of sensitivity to the device structure's fissures.



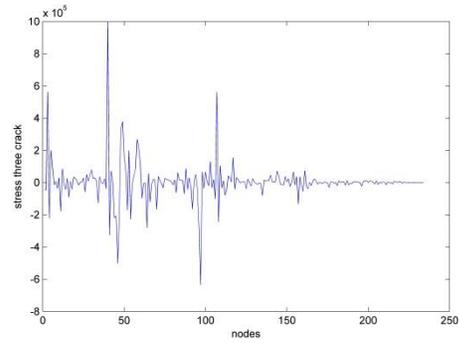
a)Healthy beam



b)Beam with 1 crack

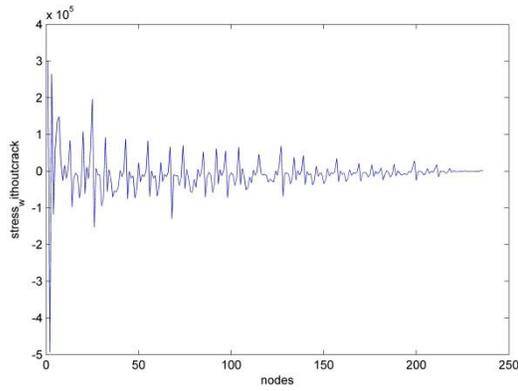


c)Beam with 2 cracks

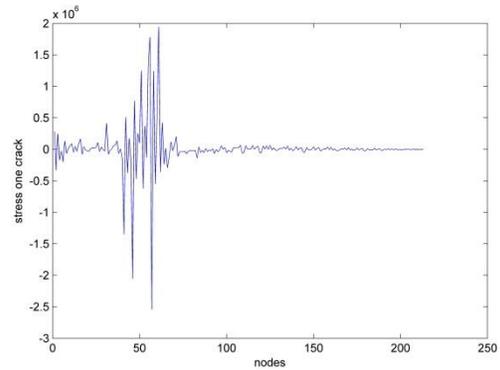


d)Beam with 3 cracks

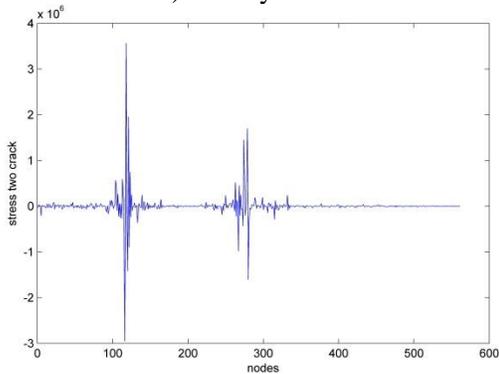
Figure.11 Wavelet coefficient of db4 wavelet



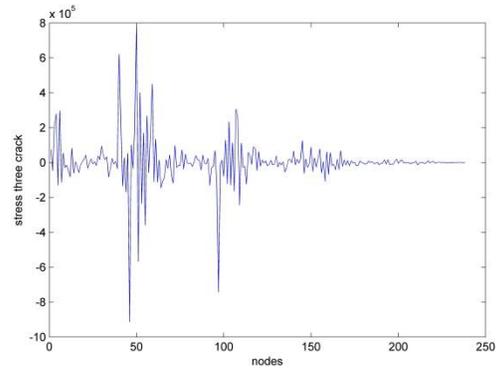
a)Healthy beam



b)Beam with 1 crack



c)Beam with 2 cracks



d)Beam with 3 cracks

Figure.12 Wavelet coefficient of db8 wavelet

6. Conclusion

Wavelet transform was suggested as a technique for locating cracks in micro cantilever beam structures. MATLAB performed wavelet transform analysis and COMSOL simulation software was used to model the device. For a variety of devices, the device features, such as displacement and stress, were investigated and contrasted. The suggested study outlines an efficient and successful technique for locating the crack site by employing Haar and Daubechies wavelet coefficients to analyze the device's output signals. This approach has shown to be the most successful in meeting the need for crack detection in structures. In this case, Haar and Daubechies wavelets are the most successful technique for crack identification since they adapt well to changes in the device's structure. Since this innovative type technique is extremely sensitive to even the smallest modifications, it can be applied to any micro device structure. In our next effort, we will investigate this type of method further for different micro structures.

References

1. P Mehta, A Kureshi, S Lad," Detection of Cracks in a Cantilever Beam Using Signal Processing and Strain Energy Based Model" IOP Conf. Series: Materials Science and Engineering, 2017
2. Mei Kobayashi, Masaharu Sakamoto," Wavelet Analysis Used in Text-to-Speech Synthesis", IEEE Transactions on Circuits and Systems, Vol. 45, No. 8, August 1998.
3. Imran Sharif, Sangeeta Khare," Comparative analysis of Haar and Daubechies wavelet for hyper spectral image classification" ISPRS Technical Commission VIII Symposium, 2014.
4. Lvchen Cao, Huiqi Li," Hierarchical method for cataract grading based on retinal images using improved Haar wavelet" Information Fusion 53,2019.
5. Amara Graps," An Introduction to Wavelets "IEEE Computational Science and Engineering, Vol 2, 1995.
6. Paul Embrechts, Agnes M. Herzberg," An introduction to wavelets with applications to Andrews' plots" Journal of Computational and Applied Mathematics,1995.
7. Daniel T.L.Lee, Akio Yamamoto, "Wavelet Analysis: theory and applications" Hewlett-Packard company,1994.
8. M. Sifuzzaman, M.R. Islam," Application of Wavelet Transform and its Advantages Compared to Fourier Transform" Journal of Physical Sciences, Vol. 13, 2009.
9. Ramon S. Y. C. Silva, Luciano M. Bezerra," Determination of Damages in Beams using wavelet Transforms" Proceedings of the World Congress on Engineering, 2012.
10. Magdalena Rucka," Damage detection in beams using wavelet transform on higher vibration modes" Journal of Theoretical and Applied Mechanics ,Warsaw, 2011.
11. Lee, Y. Y., Liew, K. M," Detection of damage locations in a beam using the wavelet analysis" International Journal of Structural Stability and Dynamics, 2001
12. M. Solis, Q. Ma," Damage detection in beams from modal and wavelet analysis using a stationary roving mass and noise estimation" John Wiley & Sons Ltd, 2018.
13. S Lucas, K Kis-Sion," Polysilicon cantilever beam using surface micromachining technology for application in microswitches", J. Micromech. Micro engg,1997.

14. B. G. Sheeparamatti, J. S. Kadadevarmath, "Electrical Equivalent Analysis of Micro Cantilever Beams for Sensing Applications" International Journal of Electronics and Communication Engineering, 2015.
15. D. Srinivasarao, K.Mallikarjuna Rao, "Crack identification on a beam by vibration measurement and wavelet analysis" International Journal of Engineering Science and Technology, 2010.
16. Chui,C.K" An introduction to wavelets, wavelet Analysis and its applications",Volume1, Academic Press, San Diego,1992.
17. Ravikumar.K, Ithaya Priya.B" Detection of cracks in Micro structured Cantilever Beam using Wavelet Transforms" International Journal of Recent Technology and Engineering, 2020.
18. Ravikumar K, Ithaya Priya B "Identification of multiple crack locations in microcantilever beam by wavelet transforms". Indian Journal of Science and Technology 13(35):3685-3694. [https://doi.org/10.17485/IJST/v13i35.1472\(2020\)](https://doi.org/10.17485/IJST/v13i35.1472(2020)).