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Continuous Vibration Monitoring System using Gaussian Beams and Artificial Neural Network

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Abstract: *Vibration monitoring is an essential tool for equipment and plant maintenance in many industries. It is possible to extend the maintenance intervals, if vibration is monitored closely. The objective of the paper is to develop a non-contact type vibration analyzer which can be used to develop a continuous monitoring of vibrations using neural networks. The vibration monitoring system consists of sensor array & holder, data acquisition board and data processing tool. In the proposed system, the Gaussian beam of laser source illuminates an array of photo detectors, which is reflected from the system undergoing vibration. These time varying optical powers are input to an artificial neural network based vibration monitoring system which maps the power distributions of the laser beam. The Neural network model for selected problem was Nonlinear Input-Output as the problem involves solving time series data from the sensors. The training was done with data from experimental setup of cantilever which was given a free vibration and the modeled cantilever vibration using ANSYS. The method of reading the vibration data is by obtaining the reflected pattern using the sensor array; these data were fed into the MATLAB. Once neural network is trained for a set of known vibrations, they can be used for analyzing unknown vibrations. The system can be further be used in monitoring the conditions of the vibrating body.*
Keywords: *Vibration monitoring, CATIA, Rapid prototyping, Artificial neural network, MATLAB*

I. Introduction

Vibrations may sometimes be devised for various processes or in most cases it is not desired and damages the machine. The vibrations may cause loss in money and time as it causes the failure of various machine parts. Vibration is inversely related to the lifetime of the machine. Low levels of vibration indicate low vibratory forces, resulting longer machine life. When the machine deteriorates and ages, the dynamic forces generated by the machine will increase in intensity, causing an increase in machine vibration. Which again causes the increased dynamic forces and by the cumulative effect the wear rate increases and reduces the machine life and increases maintenance cost. It is of at most importance to measure vibrations and control them if it crosses the limit. Hence vibration measurement is a major area of focus in the past few decades.The four factors that determine the characteristics of vibration are: the excitation force (which is due to the unbalance or looseness), mass of the vibrating system, stiffness of the vibrating system and damping characteristics of the vibrating system. The last three factors absorb, stop or minimize the vibration whereas the first factor causes the vibration. Vibrations can be predominantly measured by contact and non-contact type transducers. The contact type vibration transducers are used where the measurement of the vibration does not cause loading error. Some examples include potentiometers, LVDT (linear variable differential transformers), strain gauges, and piezoelectric accelerometers. Non-contact type transducers, are used where the instrument should not interfere with the object to be measured. The most common ones are capacitive, inductive, magnetic, or optical. Non-contact optical measuring techniques are regions of interest in recent years. They can be directed at targets that are difficult to access or hazardous, too small or too hot to attach a physical transducer on. Such sensors include Fabry–Perot interferometers, fiber Bragg grating arrays, and laser Doppler vibrometry. The interferometers utilize the interference pattern between the reflected laser and the coherent source to detect the vibration pattern of the grating arrays.The fiber Bragg grating arrays produces a shift in wavelength according to the vibration amplitude.The laser Doppler vibrometry user the relative shift in the frequency of the laser to identify the vibration velocity. However, one of the major disadvantage of laser Doppler vibrometry sensors is that they have to be calibrated very accurately as they are range dependent and the distance that they measure has to be precisely defined. Also the laser Doppler vibrometer requires a very high resolution to limit the signal to noise ratio. The noises in the Laser Doppler vibrometry include light induced noise (shot noise), Thermal Induced Noise (Johnson noise) and the signal processing noise. The present vibration systems require continuous monitoring and the whole process of vibration analysis has to be carried out periodically. Since, we have currently packages like neural network which if trained properly could do this time consuming and cumbersome task by itself, present technologies require such modifications.

The objective of the paper is to develop a non-contact type vibration analyzer which can be used for continuous monitoring of vibrations with neural network. The main objective of the device is to generate and analyze the vibration pattern of the object using laser and the position sensitive detector array. A brief introduction is given into Section 1, followed by methodology including the product development and data collection of the project is highlighted in Section 2. Section 3 provides the theoretical background for the project. Section 4 deals with results and last, the conclusions are provided in Section 5.

Methodology

Fig.1 shows the study methodology. Firstly, the design of the sensor array and laser holder were created in CATIA v5 after taking the accurate dimensions of laser and the photo sensors using an electronic caliper. The design was then imported to the Rapid Prototyping (RP) machine for fabrication. The orientation that required the least manufacturing time was chosen and sent for fabrication in the RP machine. The part was produced in the base material, and for its removal, the part was kept in a support cleaning machine in which a solution of water and ecoworks^{tm} tablets were simultaneously heated and stirred. The parts, thus separated from the support material were then assembled using soldering and bolting. The experimental setup consisting of inducing vibration to cantilever was created thereafter. Laser beams were focused onto this vibrating cantilever and the reflected rays fell on the photo sensor array. The time varying optical signals which was converted to varying voltage signal at each elements of the sensor array was read using Arduino board, interfacing the photo sensor with MATLAB software. Since MATLAB can process only discrete signals and the signals from photo sensor array were continuous signals, codes were generated for this specific purpose. The data were read into MATLAB this way and was analyzed and different patterns were generated with different time intervals. With these data, the neural network interface was trained. This was done in the neural network tool available in the MATLAB. Thus the vibrations patterns of any unknown signals can be analyzed thereafter.

2.1 Experimental Setup

Fig.2 shows the experimental setup. The experimental setup consists of a laser source with an average power of 2 mW. The beam is focused on an array of five photo detectors. The laser beam spot diameter is calibrated using the collimator optics to be concentric, and totally contained within the photo detector cell. The laser holder was designed in CATIA as shown in Fig.3. Photo detectors convert the optical power to an electrical current. Each photo detector is connected to a signal conditioning circuit which involves amplification, noise filtering, and bias removal. The main source of measurement noise is due to ambient light conditions. Thermal shot noise processes were proven to be negligible in such a setup.

2.2 Rapid Prototyping of Measuring Device

Rapid prototyping (RP) are techniques for easy fabrication of scale model of a physical part or assembly using data available in the models created in CAD. Various techniques are used in creating the prototyping recent developments are mainly concentrated on “additive layer manufacturing” technology because of the easiness of the method and availability of 3D printers. Material used in RP machine is ABS. The three-dimensional computer aided design is done using CATIA v5 software. The 3D data is converted into stl file and is printed in the RP machine (MOJO make). After manufacturing of the part in Rapid Prototyping machine, it was kept in support cleaning machine to separate the part from the frame and base material. The part was kept in a solution of water and Ecoworks^{TM} tablets was simultaneously heated and stirred. Ecoworks^{TM} cleaning agent is designed to remove support materials from models built using the FDM process with SR-10 (P400-SR), SR-20, or SR-30 soluble support materials. The cleaning agent is both user and eco-friendly. No personal protection equipment is required when handling the cleaning agent and disposal of the used solution requires only dilution with clean water to meet generally acceptable world- wide disposal standards. The parts obtained after manufacturing in RP machine are shown in Fig.4. The developed parts are then assembled and necessary accessories such as laser, sensors (photo transistors), arduino board, etc. were properly placed (Fig.5).

2.3 Modal analysis of Cantilever Beam

For the successful training of the neural network we require a set of required values and compare them with the data obtained from the sensor array. These values are then used to train the neural network by comparing the output value with the required values. Thus a neural network model of the required vibrometer is obtained through continuous update of network according to the training data. For obtaining the actual values for the training we modelled a steel ruler and considered it as the cantilever beam. The design of the cantilever was done in the CATIA v5 and analysis was done in the ANSYS software. One end was given rigid constraint so as to make it as a cantilever and was given several modes of vibration and the corresponding oscillations were obtained. From the analysis results the 1st natural frequency of the model was found out and the model was made to vibrate in the natural frequency and samples of the amplitude were obtained at fixed intervals. Fig.6 shows the modal analysis in ANSYS. This is imported into the MATLAB and was used as the reference for the neural network.

2.4 Data collection

Data is fed into the computer from the sensor array by means of an arduino board. Arduino uno is first installed in MATLAB. The data is then entered into the MATLAB through suitable codes generated for this specific purpose. The actual data read from the sensor are imported into the MATLAB directly from the Arduino software using the Arduino package. These data correspond to the voltage level at each sensor are converted using ADC available in the Arduino and data is imported into MATLAB in the required intervals.In the experimental setup, the laser beam is made to strike on the system which is subjected to vibration at the 1st natural frequency. The laser beam gets reflected from the vibrating system and this reflected beam strikes on the sensor array. The laser can be adjusted on the laser holder and can be oriented so that the laser beam strikes the vibrating system and then reflects back to the sensor array itself. If the vibrating system is not a good reflector of laser beam, the laser beam can be reflected by sticking a reflective material to the vibrating body (reflecting paper, mirror, sheet metal etc.). The vibration patterns are different for defective system and a perfectly working system. Firstly we analyze the vibration patterns of a perfectly working system. These data are read into a MATLAB variable and are used for training the neural network. We then train the neural network for various vibrations. Thus the function for the vibration measurement device is obtained. Now various vibration patterns can be read and measured using the device. Now we test an unknown system. The data from unknown vibration is processed using the neural network and the final results are recorded. The vibration patterns various systems are analyzed and compared with each other. Thus an equipment or system can be checked for its defect by using this method. For analyzing the defected system the data from the perfectly working system is analyzed 1st and is recorded this data is compared with the other systems and the defective systems can be identified using the vibration pattern changes.

2.5 ARDUINO codes

The signals from the photo sensor array are obtained in the arduino board as continuous signals (Fig.7). This data from the arduino board has then to be fed into the MATLAB for further processing. Albeit, MATLAB could process only discrete signals.This initiated the need for developing a code to convert the continuous signals into discrete signals so that it can be analyzed in the MATLAB.

2.6 Neural Network

To model the highly nonlinear system a mathematical model is very difficult hence a non-parametrical model is obtained by using the neural network. A neural network model can successfully represent the process affected by external operating conditions and several process parameters often unknown. ANN gives a highly data-driven, self- adaptive, flexible computational method having ability to absorb nonlinear and complex relations. They can be considered as a system in which a set of inputs are linked to the outputs because of its flexibility to adapt to changes they are widely used in industries, they have been used in vibration monitoring applications by many research groups. For developing the actual model of the system we require a great deal of calculations and understanding of the phenomenon of the laser light which is obtained by assuming the laser to have a normal distribution of the spot from its centre placement of the sensors the refraction, reflection and absorption of the laser by the ABS material, the shape of the reflector etc. Apart from the previously mentioned advantages, ANN algorithms have also the advantage to be easily implemented in parallel architectures (i.e., in multicore processors) which drastically reduces the processing time.

- Inputs and Target data:The input to the neural network is a set of discrete signals obtained from the photo sensor array. The target data is the transient response in the required coordinates.
- Validation and Test data: These are used to measure network generalization, and to halt training when generalization stops improving.
- Network Architecture: Network architecture helps to choose the number of neurons and input delays. It displays the structure of hidden layer with delays and output layers.
- Neural Network Training: With the given data, the neural network is trained to produce the required output which can be in the form of a function, a transient response or Simulink diagram.
- Deployable versions of Trained Neural Network: The deployable versions include application deployment, code generation, Simulink deployment and graphics.

For the training of the neural network the input and output of the neural network is required. The input of the neural network is obtained by the vibration data read by the sensors and the output required is calculated from the CAD model of the vibratory system. This data are given for the training of the neural network and the resultant network is used for the vibration monitoring. Code for reading the data into a variable is shown in Fig.8.

3. Theory

Doppler effect is the change in frequency of a wave, for an observer moving relative to the source. When light wave strikes on a body, it gets reflected. If the body is vibrating, then there will be a Doppler effect since the body surface (on which light wave strikes and reflects) doesn't remains constant. This frequency patterns will be different for different objects. We have two bodies, one being a standard body and assumed to be an ideal one (without any defects) and the other body is the one which is to be tested. If there is any defect in the second body to be tested, then the light waves reflecting from the both bodies will differ. By analyzing the frequency patterns of the defective part and comparing it with the standard part, faults can be detected easily. The reflected light is then allowed to fall on the photo sensor cells. The photo sensor array holder is made of parabolic shape so that the focal point of the parabolic is exactly at the point where the photo sensor cells are arranged.

4. Results

The system developed can be used to identify and classify the various vibration patterns of any machine. Thus the condition of the machine can be monitored closely. The proposed system was designed in CATIA v5 and manufactured from ABS material using RP machine. The sensor array was developed with accurate dimensions from electronic calliper and was given a parabolic shape, so that the rays falling on the parabolic surface gets reflected to the focal point where sensors are placed. Since the sensor array was designed
from the nature of the vibration the resolution can be increased by placing more sensors and arranging them accordingly. From the modal analysis of the cantilever beam it was found that maximum amplitude of oscillation occurred at the free end as expected and its magnitude was determined for different modes of vibration. The data for the primary degree of vibration was obtained from the ANSYSTM software and was obtained as the displacement from the lowest position. The data obtained for the same from the sensors are then

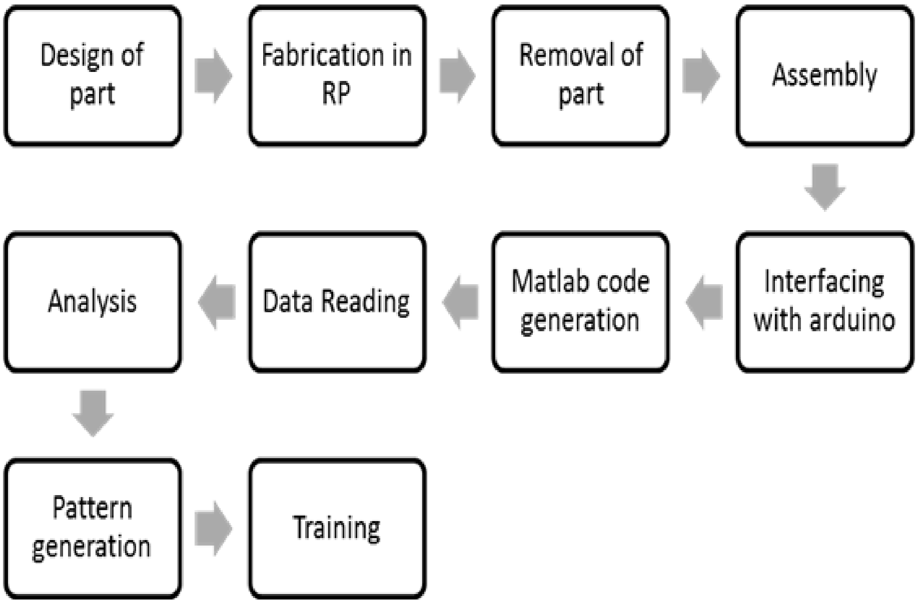

Fig.1 Study methodology

Provided to the neural network for training. Codes generated contributed to the interfacing of data from arduino to MATLAB by converting continuous signals into discrete signals. These data are stored in the process or by means of neural network. We then train the neural network for various vibrations. Then we test a faulty system. The vibration patterns of this defective system are analyzed and are compared with the previously recorded data of the proper system. Neural network compares these data and gives the corresponding vibration. Thus an equipment or system can be checked for its defect by using this method. For example, the trial data obtained during random testing were shown in Fig.9. These graphs show the transient response of amplitude for different trial signals. The variation in the values from same laser source are due to the difference in the intensity of the laser signals striking on the sensor arrays, as intensity increases the amplitude increases and vice versa.

II. Figures And Tables

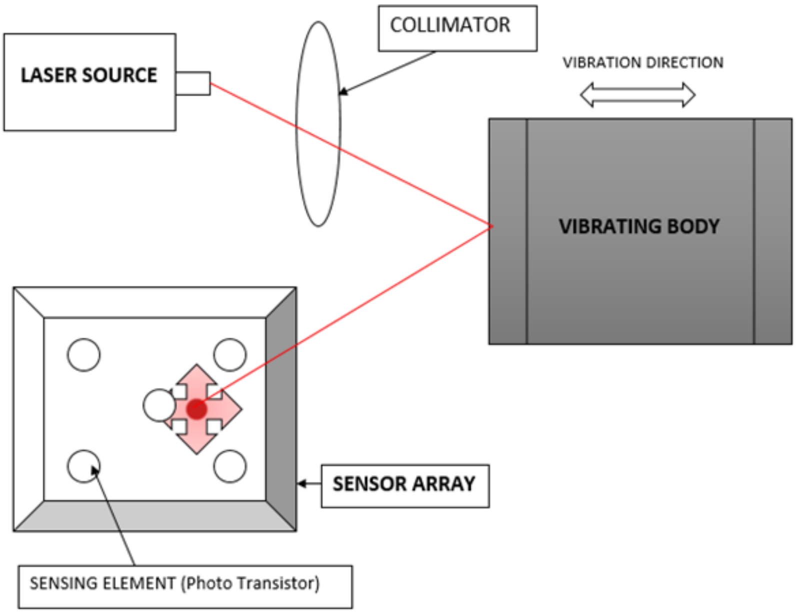

Fig.2 Experimental block diagram

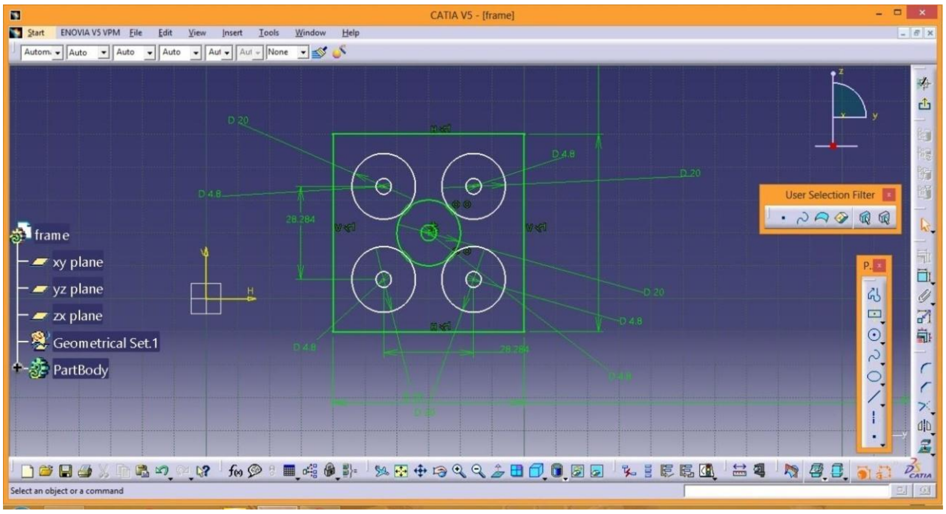

Fig.3 Design of laser holder in CATIA v5

Fig.4 Sensor array, laser frame and laser holder after rapid prototyping

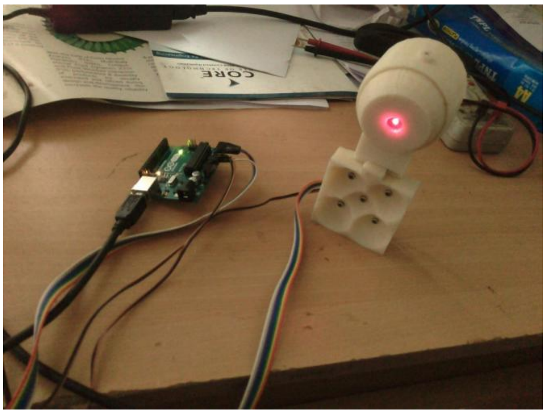

Fig.5 Assembly of laser holder, sensor array and arduino board

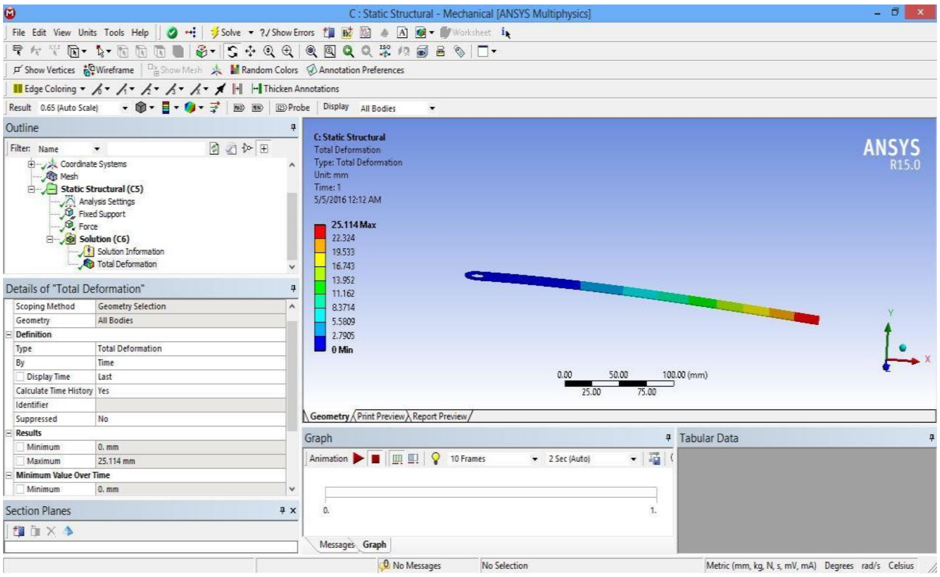

Fig.6 Solution of modal analysis

```
Clc             //clears screen
a=arduino       //links Arduino to a variable a
i=1;
whilei<1000    //for reading analog voltages from sensors
sensor1(i)=readVoltage(a,'A0');
sensor2(i)=readVoltage(a,'A1');
sensor3(i)=readVoltage(a,'A2');
sensor4(i)=readVoltage(a,'A3');
sensor5(i)=readVoltage(a,'A4');
i=i+1;
end
subplot(3,2,1);     //plot the data obtained
plot(sensor1); title('Subplot1:Sensor1')
subplot(3,2,2);
plot(sensor2); title('Subplot2:Sensor2')
subplot(3,2,[3,4]);
plot(sensor3); title('Subplot3:Sensor3')
subplot(3,2,5);
plot(sensor4); title('Subplot4:Sensor4')
subplot(3,2,6);
plot(sensor5); title('Subplot5:Sensor5')
```

Fig.7 Arduino code

```
clc
a=Arduino
i=1;
sensor=zeros(5,1);
sensorcell=cell(1,672)

whilei<673
sensor(1,1)=readVoltage(a,'A0');
sensor(2,1)=readVoltage(a,'A1');
sensor(3,1)=readVoltage(a,'A2');
sensor(4,1)=readVoltage(a,'A3');
sensor(5,1)=readVoltage(a,'A4');
```

Fig.8 Code for reading the data into a variable

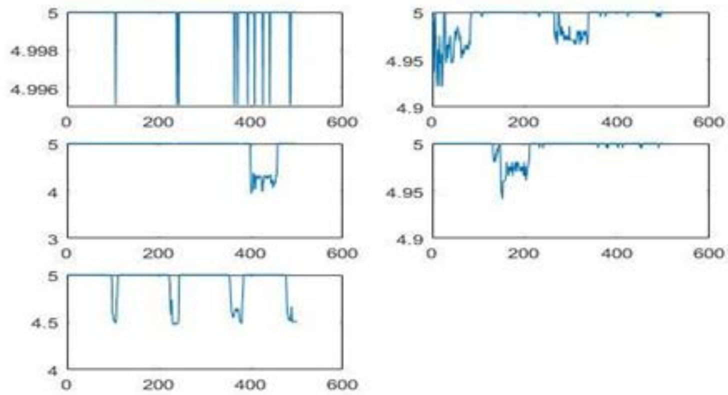

Fig.9 Sample plots obtained from a random vibration from all 5 sensors

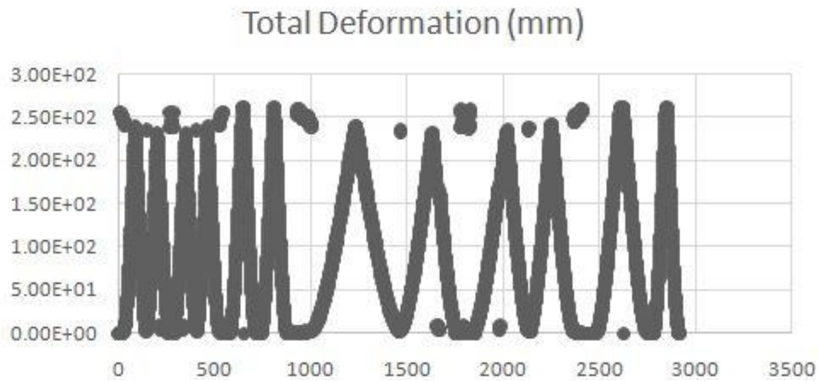

Fig.10 Plot obtained from ANSYS™

III. Conclusion

This paper introduces an optical vibration monitoring system based on Gaussian laser beam optics and artificial neural networks. The estimated frequencies by the neural network are shown to be within 1% of the actual system frequencies of vibration. However, the error on the estimated magnitude of vibration can be high, if the proper training stimulus is not used. On the other hand it is found that training the neural network with a decaying chirp signal, reduces this magnitude error. Even though the neural network estimates the frequency quite accurately the magnitude variations will depend on the quality of the photo detector outputs. In addition, in the proposed experimental setup the coupling between the laser source and the collimator introduces relatively high losses, suggesting that further improvements in the signal to noise ratio can be achieved if the coupling issue is overcome. Using a laser with higher power output is also expected to improve the vibration magnitude estimation. The range of the magnitude range can be further increased by using larger photo sensor detector arrays which can cover more area. Now, we have only considered frequency. Further amplitude can also be analysed for considering vibration.

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