VIBRATION ANALYSIS OF STRUCTURES

A THESIS SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE DEGREE OF

Bachelor of Technology

In Civil Engineering

By

Govardhana Rao

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DEPARTMENT OF CIVIL ENGINEERING

iNATIONAL INSTITUTE OF TECHNOLOGY ROURKELA

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Under the Guidance of

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National Institute of Technology
Rourkela

CERTIFICATE

This is to certify that the thesis entitled, "VIBRATION ANALYSIS OF STRUCTURES" submitted by Shri Govardhana rao Boddu in partial fulfillments for the requirements for the award of Bachelor of Technology Degree in Civil Engineering at National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Date:11-05-2009

Prof.U.K. MISHRA
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ACKNOWLEDGEMENT

I would like to express my deepest gratitude to my guide and motivator Prof. U.K.Mishra, Professor, Civil Engineering Department, National Institute of Technology, Rourkela for his valuable guidance, sympathy and co-operation for providing necessary facilities and sources during the entire period of this project.

I wish to convey my sincere gratitude to all the faculties of Civil Engineering Department who have enlightened me during my studies. I am also thankful to the Structural Engineering Laboratory, NIT Rourkela for helping me during the experiments.

Govardhana Rao. Boddu

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Final Yr, Civil Engineering,

N.I.T ROURKELA.

Date: 11thMay, 2009

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CHAPTER 1

FINITE ELEMENT METHOD

FINITE ELEMENT METHOD

1.1 INTRODUCTION Theory

1.1.1 Where this Material Fits

The field of Mechanics can be subdivided into three major areas:

Mechanics
- *Theoretical*
- *Applied*
- *Computational*

Theoretical mechanics deals with fundamental laws and principles of mechanics studied for their intrinsic scientific value. *Applied mechanics* transfers this theoretical knowledge to scientific and engineering applications, especially as regards the construction of mathematical models of physical phenomena. *Computational mechanics* solves specific problems by simulation through numerical methods implemented on digital computers.

1.1.2Computational Mechanics

Several branches of computational mechanics can be distinguished according to the physical scale of the focus of attention:

Computational Mechanics
- *Nanomechanics and micromechanics*
- *Continuum mechanics*
  - Solids and Structures
  - Fluids
  - Multiphysics
- *Systems*

Nano mechanics deals with phenomena at the molecular and atomic levels of matter. As such it is closely linked to particle physics and chemistry. Micro mechanics looks primarily at the crystallographic and granular levels of matter. Its main technological application is the design and fabrication of materials and micro devices. Continuum mechanics studies bodies at the macroscopic level, using continuum models in which the microstructure is homogenized by phenomenological averages. The two traditional areas of application are solid and fluid mechanics. The former includes structures which, for obvious reasons, are fabricated with solids. Computational solid mechanics takes an applied sciences approach, whereas computational structural mechanics emphasizes technological applications to the analysis And design of structures.

Computational fluid mechanics deals with problems that involve the equilibrium and motion of liquid and gases. Well developed subsidiaries are hydrodynamics, aerodynamics, acoustics, atmospheric physics, shock, combustion and propulsion.

A system is studied by *decomposition*: its behavior is that of its components plus the interaction between components. Components are broken down into subcomponents and so on. As this hierarchical breakdown process continues, individual components become simple enough to be treated by individual disciplines, but component interactions get more complex.

1.1.3Statics vs. Dynamics

Continuum mechanics problems may be subdivided according to whether inertial effects are taken into account or not:

$$\text{Continuum mechanics} \begin{cases} \textit{Statics} \\ \textit{Dynamics} \end{cases}$$

In dynamics actual time dependence must be explicitly considered, because the calculation of inertial (and/or damping) forces requires derivatives respect to actual time to be taken.

Problems in statics may also be time dependent but with inertial forces ignored or neglected. Accordingly static problems may be classed into strictly static and quasi-static. For the former time need not be considered explicitly; any historical time-like response ordering parameter, if one is needed, will do. In quasi-static problems such as foundation settlement, metal creep, rate-dependent plasticity or fatigue cycling, a realistic measure of time is required but inertial forces are still neglected.

1.1.4 Discretization methods

A final classification of CSM static analysis is based on the discretization method by which the continuum mathematical model is discretized in space, *i.e.*, converted to a discrete model with a finite number of degrees of freedom:

$$\text{Spatial discretization method} \begin{cases} \textit{Finite Element (FEM)} \\ \textit{Boundary Element (BEM)} \\ \textit{Finite Difference (FDM)} \\ \textit{Finite Volume (FVM)} \\ \textit{Spectral} \\ \textit{Meshfree} \end{cases}$$

In CSM linear problems finite element methods currently dominate the scene as regards space discretization. Boundary element methods post a strong second choice in specific application areas. For *nonlinear* problems the dominance of finite element methods is overwhelming.

1.1.5 FEM Variants

The term Finite Element Method actually identifies a broad spectrum of techniques that share common features outlined in above sections. Two sub classifications that fit well applications to structural mechanics are

$$\text{FEM Formulation} \begin{cases} \textit{Displacement} \\ \textit{Equilibrium} \\ \textit{Mixed} \\ \textit{Hybrid} \end{cases} \qquad \text{FEM Solution} \begin{cases} \textit{Stiffness} \\ \textit{Flexibility} \\ \textit{Mixed (a.k.a. Combined)} \end{cases}$$

Of the variants listed above, emphasis is placed on the displacement formulation and stiffness solution. This combination is called the Direct Stiffness Method or DSM.

1.2 The Finite Element Method

A promising approach for developing a solution for structural vibration problems is provided by an advanced numerical discretisation scheme, such as, finite element method (FEM).The finite element method (FEM) is the dominant discretization technique in structural mechanics.

The basic concept in the physical FEM is the subdivision of the mathematical model into disjoint (non-overlapping) components of simple geometry called *finite elements* or *elements* for short. The response of each element is expressed in terms of a finite number of degrees of freedom characterized as the value of an unknown function, or functions, at a set of nodal points. The response of the mathematical model is then considered to be approximated by that of the discrete model obtained by connecting or assembling the collection of all elements.

A straight beam element with uniform cross section is shown in Figure.1. The Euler-Bernoulli beam theory is used for constituting the finite element matrices. The longitudinal axis of the element lies along the x axis. The element has a constant moment of inertia I, modulus of elasticity E, density r and length l . Two degrees of freedom per node, translation along y-axis (y1, y2) and rotation about z-axis ($y_1^{|}$,$y_2^{|}$) are considered.

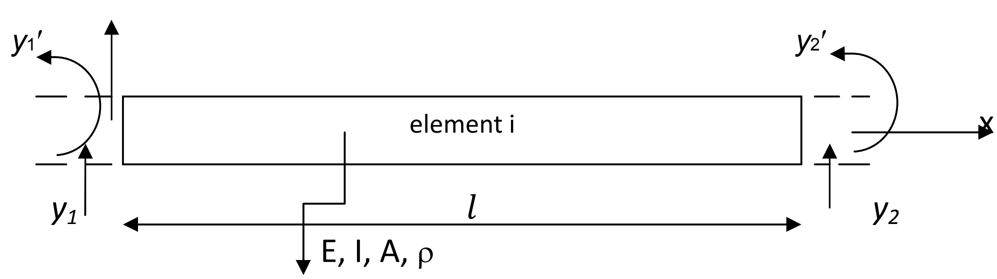

Figure.1 straight beam element

Strain energy of a single element is:

S.E. = $\int_0^l \frac{EI}{2}\left(\frac{\partial y^2}{\partial x^2}\right)$dx ……… (1)

Kinetic Energy of a single element is:

K.E. = $\int_0^l \frac{\rho A}{2}(\frac{\partial y}{\partial t})^2$ ……… (2)

A cubic function, y(x,t), is assumed for the transverse displacements as

y(x,t) = a_0(t) + a_1(t)x + a_2(t)x2 + a_3(t)x3 ……...(3)

Where a_0(t), a_1(t), a_2(t) and a_3(t) are obtained by applying the boundary conditions at the corresponding nodes, so the shape functions are represented as

$N_1(x) = 1 - 3(\frac{x}{l})^2 + 2(\frac{x}{l})^3$ ……..(4)

$N_2(x) = x - 2l(\frac{x}{l})^2 + l(\frac{x}{l})^3$

$N_3(x) = 3(\frac{x}{l})^2 - 2(\frac{x}{l})^3$

$N_4(x) = -l(\frac{x}{l})^2 + l(\frac{x}{l})^3$

At x=0 y_1 = a_0 $\dot{y_1}$=a_1

At x= l y_2 = a_0+a_1 l + a_2 l^2 +a_3 l^3 $\dot{y_2}$= a_1+2$a_2 l$ + a_3 l^2

$$\begin{bmatrix} y_1 \\ \dot{y_1} \\ y_2 \\ \dot{y_2} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix}$$

{y}= [C]{a}

$\{a\} = [C^{-1}]\ \{y\}$

$$y = [x]\ \{a\} = [1 \quad x \quad x^2 \quad x^3] \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = [x][C]\ \{y\}$$

$\frac{\partial y}{\partial t} = [X][C^{-1}]\ \{y\}$ and $\frac{\partial y^2}{\partial x^2} = \{\frac{\partial y}{\partial t}\}^T\ \{\frac{\partial y}{\partial t}\}$

$$K.E = \int_0^l \rho A \{\dot{y}\}^T [c]^{-T} \begin{bmatrix} 1 \\ x \\ x^2 \\ x^3 \end{bmatrix} [1 \quad x \quad x^2 \quad x^3][C^{-1}]\{\dot{y}\}\ dx$$

From the above equation we find the mass matrix as follow:

$$\mathbf{M} = \frac{\rho A l}{420} \begin{bmatrix} 156 & 22l & 54 & -13l \\ 22l & 4l^2 & 13l & -3l^2 \\ 54 & 13l & 156 & -22l \\ -13l & -3l^2 & -22l & 4l^2 \end{bmatrix}$$

$S.E. = \int_0^l \frac{EI}{2} \left(\frac{\partial y^2}{\partial x^2}\right) dx$ (from equation 1)

$\frac{\partial y^2}{\partial x^2} = [0 \quad 0 \quad 2 \quad 6x][C^{-1}]\ \{y\}$

$$S.E. = \int_0^l EI\ \{y\}^T [c]^{-T} \begin{bmatrix} 0 \\ 0 \\ 2 \\ 6x \end{bmatrix} [0 \quad 0 \quad 2 \quad 6x]\ [C^{-1}]\ \{y\}$$

$\frac{\partial y^2}{\partial x^2}$=$[0 \quad 0 \quad 2 \quad 6x][C^{-1}]\ \{y\}$

S.E. = $\int_0^l EI\ \{y\}^T [c]^{-T} \begin{bmatrix} 0 \\ 0 \\ 2 \\ 6x \end{bmatrix} [0 \quad 0 \quad 2 \quad 6x]\ [C^{-1}]\ \{y\}$

From the above equation we find the stiffness matrix as follow:

K= $\frac{EI}{l^3}\begin{bmatrix} 12 & 6l & -12 & 6l \\ 6l & 4l^2 & -6l & 2l^2 \\ -12 & -6l & 12 & -6l \\ 6l & 2l^2 & -6l & 4l^2 \end{bmatrix}$

Equations of Motion of the Beam:

The equation of motion for a multiple degree of freedom undamped structural system is represented as follows

[M] $\{\ddot{y}\}$ + [K]{y}= {F(t)}

Where $\ddot{y}$ and y are the respective acceleration and displacement vectors for the whole structure and {F(t)} is the external force vector.

Under free vibration, the natural frequencies and the mode shapes of a multiple degree of freedom system are the solutions of the eigenvalue problem.

[[K]−$\omega^2[M]$] {Φ} = 0

where ω is the angular natural frequency and Φ is the mode shape of the structure for the corresponding natural frequency.

CHAPTER 2

DYNAMIC ANALYSIS

2.1 Introduction

Civil engineering structures are always designed to carry their own dead weight, superimposed loads and environmental loads such as wind or waves. These loads are usually treated as maximum loads not varying with time and hence as static loads. In some cases, the applied load involves not only static components but also contains a component varying with time which is a dynamic load. In the past, the effects of dynamic loading have often been evaluated by use of an equivalent static load, or by an impact factor, or by a modification of the factor of safety.

Many developments have been carried out in order to try to quantify the effects produced by dynamic loading. Examples of structures where it is particularly important to consider dynamic loading effects are the construction of tall buildings, long bridges under wind-loading conditions and buildings in earthquake zones, etc.

Typical situations where it is necessary to consider more precisely the response produced by dynamic loading are vibrations due to equipment or machinery, impact load produced by traffic, snatch loading of cranes, impulsive load produced by blasts, earthquakes or explosions. So it is very important to study the dynamic nature of structures.

Dynamic characteristics of a damaged and undamaged body are, as a rule, different. This difference is caused by a change in stiffness and can be used for the detection of damage and for the determination of its parameters (crack magnitude and location).

Many mechanical structures in real service conditions are subjected to combined or separate effects of the dynamic load, temperature and corrosive medium, with a consequent growth of fatigue cracks, corrosive cracking and other types of damage. The immediate visual detection of damage is difficult or impossible in many cases and the use of local non-destructive methods of damage detection requires time and "financial expense and frequently is inefficient.

In this connection, the use of vibration methods of damage diagnostics is promising. These methods are based on the relationships between the vibration characteristics (natural frequencies and mode shapes) or peculiarities of a non-linear vibration system behavior (for example, non-linear distortions of the displacement wave in different cross-sections of a beam, the amplitudes of sub-resonance and super resonance vibrations, the anti-resonance frequencies, etc.) and damage parameters. It is important to note that the essential non-linearity of vibrations of a body with a fatigue crack is due to the change of stiffness at the instant of crack opening and closing and is the main difficulty in the solution of such class problems. The analytical Investigation of vibrations of damaged structures is a complicated Problem. This problem may be simplified if a structure can be represented in the form of a beam with corresponding boundary and loading conditions. This class of structures can include bridges, offshore platforms, pipelines, masts of electricity transmission, TV towers, aircraft wings, blades and rotors of turbine engines, propellers of helicopters and many others.

Depending on the assumptions adopted, the type of analysis used, the kind of the loading or excitation and the overall beam characteristics, a variety of different approaches have been reported in the literature and a great number of both theoretical and experimental findings are related to beam dynamics.

The present study of vibration analysis of cantilever beam uses the tool Brüel*&Kjær PULSE*™, Multi-analyzer System Type 3560 for generating the vibration spectrum and to get results for various structural elements.

2.2 Vibrations

- **Vibrations::** Vibration are time dependent displacements of a particle or a system of particles w.r.t an equilibrium position. If these displacements are repetitive and their repetitions are executed at equal interval of time w.r.t an equilibrium position the resulting motion is said to be periodic.

One of the most important parameters associated with engineering vibration is the natural frequency.. Each structure has its own natural frequency for a series of different modes which control its dynamic behavior. Whenever the natural frequency of a mode of vibration of a structure coincides with the frequency of the external dynamic loading, this leads to excessive deflections and potential catastrophic failures. This is the phenomenon of ***resonance***. An example of a structural failure under dynamic loading was the well known Tacoma Narrows Bridge during wind-induced vibration.

In practical application the vibration analysis assumes great importance. For example, vehicle-induced vibration of bridges and other structures that can be simulated as beams and the effect of various parameters, such as suspension design, vehicle weight and velocity, damping, matching between bridge and vehicle natural frequencies, deck roughness etc., on the dynamic behavior of such structures have been extensively investigated by a great number of researchers . The whole matter will undoubtedly remain a major topic for future scientific research, due to the fact that continuing developments in design technology and application of new materials with improved quality enable the construction of lighter and more slender structures, vulnerable to dynamic and especially moving loads.

Every structure which is having some mass and elasticity is said to vibrate. When the amplitude of these vibrations exceeds the permissible limit, failure of the structure occurs. To avoid such a condition one must be aware of the operating frequencies of the materials under various conditions like simply supported, fixed or when in cantilever conditions.

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Classification of vibration

Vibration can be classified in several ways. Some of the important classification are as follows ::

- **Free and forced vibration** :: If a system, after an internal disturbance, is left to vibrate on its own, the ensuing vibration is known as free vibration. No external force acts on the system. The oscillation of the simple pendulum is an example of free vibration.

  If a system is subjected to an external force (often, a repeatating type of force), the resulting vibration is known as forced vibration. The oscillation that arises in machineries such as diesel engines is an example of forced vibration.

If the frequency of the external force coincides with one of the natural frequencies of the system, a condition known as resonance occurs, and the system undergoes dangerously large oscillations. Failuers of such structures as buildings, bridges, turbines and airplane have been associated with the occurrence of resonance.

- **Undamped and damped vibration** :: If no energy is lost or dissipated in friction or other resistance during oscillation, the vibration is known as undamped vibration. If any energy lost in this way, however, it is called damped vibration.In many physical system,the amount of damping is so small that it can be disregrated for most engineering purposes. However, consideration of damping become extermely important in analyzing vibratory system near resonance.

- **Linear and nonlinear vibration** :: If all the basic components of vibratory system—the spring, the mass and the damper—behave lineraly, the resulting vibration is known as linear vibration.If however,any af the basic components behave non linearly, the vibration is called non linear vibration.

Crack ::

A crack in a structural member introduces local flexibility that would affect vibration response of the structure. This property may be used to detect existence of a crack together its location and depth in the structural member. The presence of a crack in a structural member alters the local compliance that would affect the vibration response under external loads.

Classification of Crack

Based on geometries , cracks can be broadly classified as follows::

Transverse crack : These are cracks perpendicular to beam axis. These are the most common and most serious as they reduces the cross section as by weaken the beam.They introduce a local flexibility in the stiffness of the beam due to strain energy concentration in the vicinity or crack tip.

Longitudinal cracks : These are cracks parallel to beam axis. They are not that common but they pose danger when the tensile load is applied at right angles to the crack direction i.e perpendicular to beam axis.

Open cracks : These cracks always remain open.They are more correctly called “notches”. Open cracks are easy to do in laboratory environment and hence most experimental work is focused on this type of crack

Breathing crack : These are cracks those open when the affected part of material is subjected to tensile stress and close when the stress is reversed . The component is most influenced when under tension . The breathing of crack results in non-linearity in the vibration behavior of the beam.

Most theoretical research efforts are concentrated on “transverse breathing” cracks due to their direct practical relevance.

Slant cracks : These are cracks at an angle to the beam axis , but are not very common . There effect on lateral vibration is less than that of transverse cracks of comparable severity.

Surface cracks : These are the cracks that open on the surface .They can normally be detected by dye-penetrates or visual inspection.

Subsurface cracks : Cracks that do not show on the surface are called subsurface cracks . Special techniques such as ultrasonic , magnetic particle , radiography or shaft voltage drop are needed to detect them .

C H A P T E R 3

EXPERIMENTAL WORK

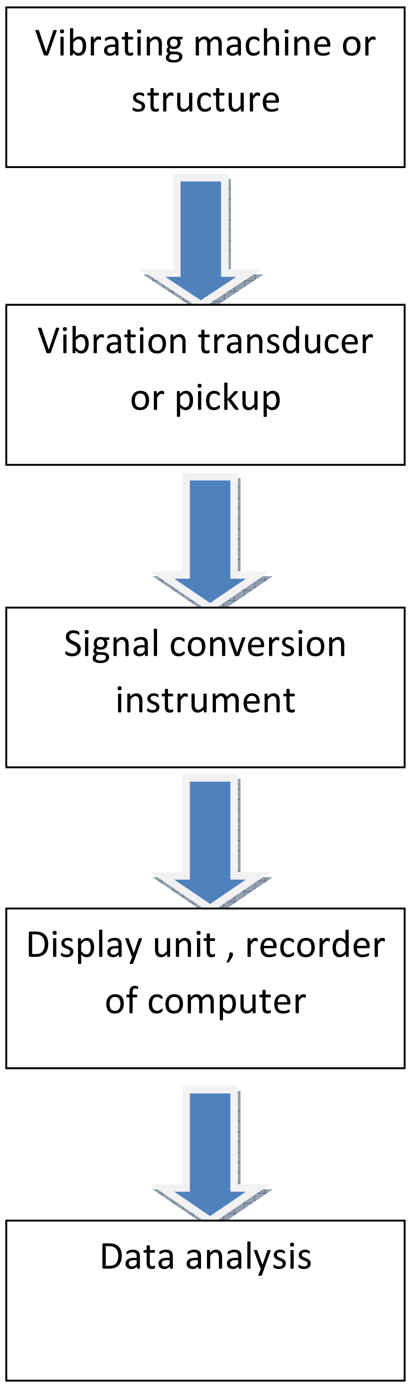
3.1 Experimental Set up:

The PULSE software analysis was used to measure the frequency ranges to which the foundations of various machines are subjected to when the machine is running with no load and full load. This will help us in designing the foundations of various machines in such a way that they are able to resist the vibration caused in them. Below we present the analysis of frequency measurements for a few cantilever beams measured in structural engineerig lab in N.I.T. Rourkela.

Equipments Required:

- Model hammer.
- Accelerometer.
- Portable pulse.
- Connectors – Model no :: AO 0087D
- Specimen.
- Display Unit.

Vibration Measurement Scheme



3.2 Equipments Description:

- ### Deltatron Accelerometer:

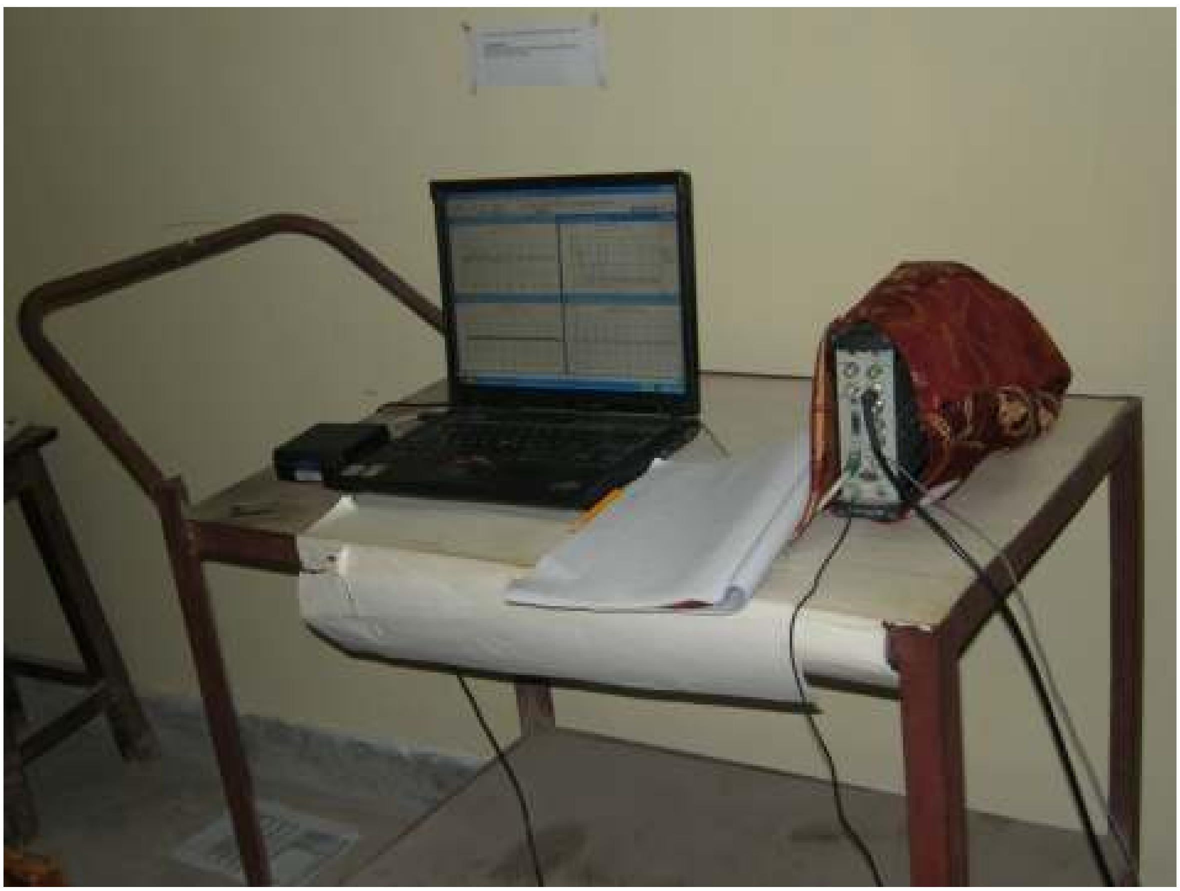
Deltatron accelerometer combines high sensitivity , low and small physical dimensions making them ideally suited for model analysis . The slits in the oscilrometer housing make it simple to mount with bee box that one easily fitted to the plate.

Model hammer

The model hammer exits the structure with a constant force over a frequency range of interest. Three interchange tips are provided which determine the width of the input pulse and thus the band width the hammer structure is acceleration compensated to avoid glitches in the spectrum due to hammer structure resonance.

Portable pulse T- type (3560C)

Bruel and kjaer pulse analyzer system type – 3560 . the software analysis was used to measure the frequency ranges to which the foundation various machines are subjected to when the machine is running with no load and full load. This will help us in designing the foundations of various machines on such a way that they are able to resist the vibration caused in them.



Display unit

This is mainly in the form of PC(Laptop) when the excitation occurs to the structure the signals transferred to the portable PULSE and after conversion comes in graphical form through the software . mainly the data includes graphs of force Vs time, frequency Vs time resonance frequency data etc.

Experimental Program

Equipments

Brüel&Kjær PULSE™, Multi-analyzer System Type 3560 was used to measure the frequency ranges of a cantilever beam.

Setup and Procedure (FFT analyzer)

- Aluminum beam of required length 40cm was cut from a bulk available beam.
- By the use of screw gauge the depth and width of beam section were measured.
- 10 cm length of beam was properly inserted to the concrete inside the mould and compacted using vibrator.
- After seven days of curing the specimen was taken out.
- Now the length of the cantilever beam from fixed end to the free end was found out.
- The connections of the FFT analyzer, laptop, transducers, model hammer along with the requisite power connections were made.
- The accelerometer -4507 type was fixed by beeswax to the cantilever beam at one of the nodal points.
- The 2302-5 modal hammer was kept ready to struck the beam at the singular points.
- Then at each point the modal hammer was struck once and the amplitude Vs frequency graph was obtained from graphical user interface.

- The FFT analyzer and the accelerometer are the interface to convert the time domain response to frequency domain. Hence the frequency response spectrumH1(response,force) was obtained.
- By moving the cursor to the peaks of the FFT graph($m/s^2/N$),the cursor values and the resonant frequencies were recorded.
- At the time of the striking with modal hammer to the singular point precautions were taken whether the striking should have been perpendicular to the aluminium beam surface.
- The above procedure is repeated for all the nodal points.
- The values (i.e., natural frequencies and resonant frequencies) obtained from the FRF spectrum were compared with respect to the FEM analysis.

3.3 Results and discussion

Beam specification::

Software used	FFT analyzer and accessories, Pulse lab shop version 9.0
parameter	frequency
Length of cantilever	20cm
Section dimensions	$0.0095X0.0095m^2$
Boundary conditions	One end fixed and another free
Material	Aluminium
Mass density	$2659kgm^{-3}$
Elastic modulus	$68.0E09Nm^{-2}$
Poison's ratio	0.205

Natural frequency of the beam was theoretically computed using the Fortran program.

Experimental results for uncracked beam:

Aluminum beam(fixed-free condition) :

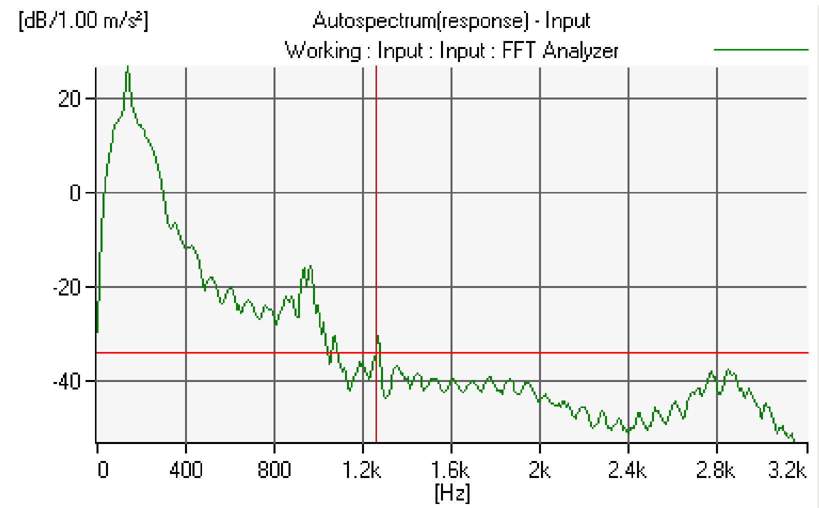
Mode	Frequency (by theoretical method)	Frequency (by practical method)	Percentage of error
first	197.42 Hz	187.00 Hz	5.27%
second	1227.66 Hz	1180.00 Hz	3.88%
Third	3393.65 Hz	3308.00 Hz	2.52%
Fourth	6547.61 Hz	6425.00 Hz	1.87%

Experimental results for single crack :

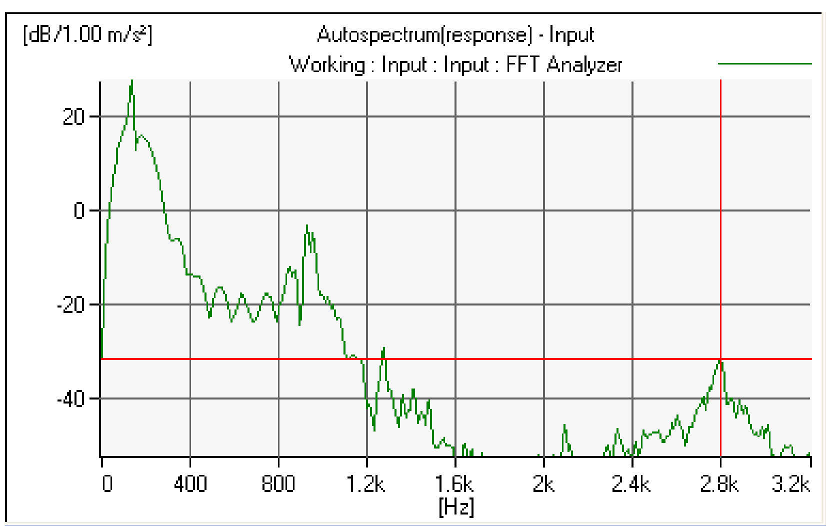
Aluminum beam(fixed-free condition)

			1st mode	2nd mode	3rd mode	4th mode
1	**Crack at centre**	**2mm**	**144**	**928**	**2088**	**2792**
2		**6mm**	**136**	**887**	**2064**	**2744**
3		**8mm**	**104**	**560**	**1448**	**2744**
4	**Crack at 0.25L**	**2mm**	**128**	**960**	**1936**	**2832**
5		**6mm**	**112**	**876**	**1720**	**2456**
6		**8mm**	**88**	**448**	**856**	**1736**
7	**No crack**	**nill**	**187**	**1180**	**3308**	**6425**

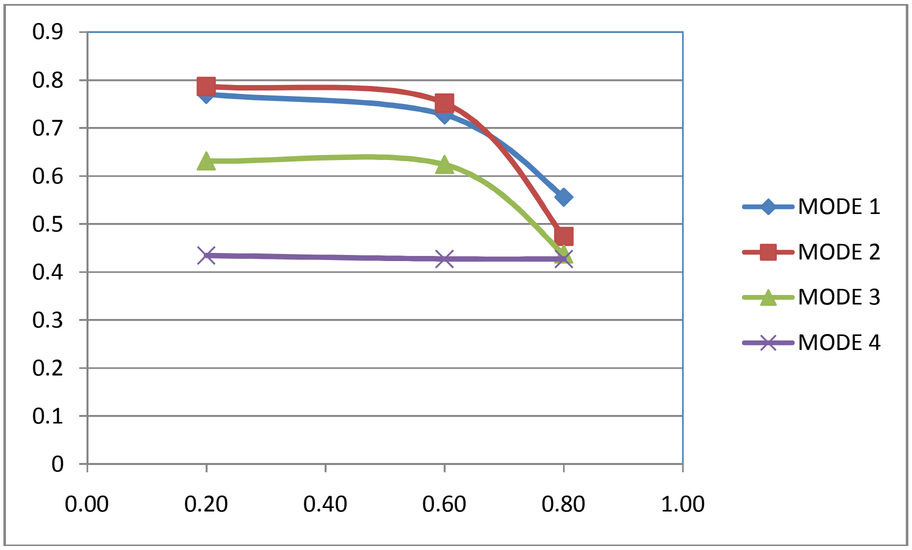
Graph for 0.25L 2mm crack::



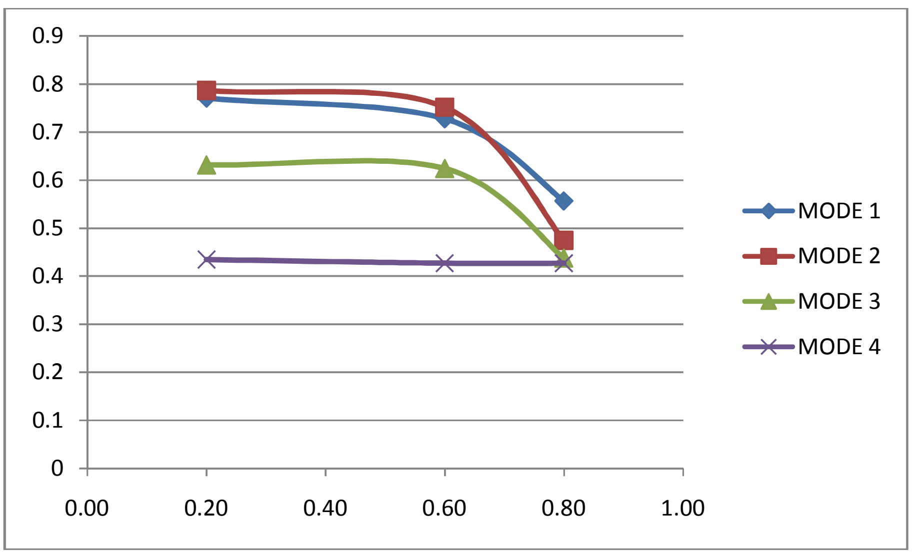
Graph for 0. 5L 2mm crack::



Crack @0.25L (single)



Crack @0.5L (single)



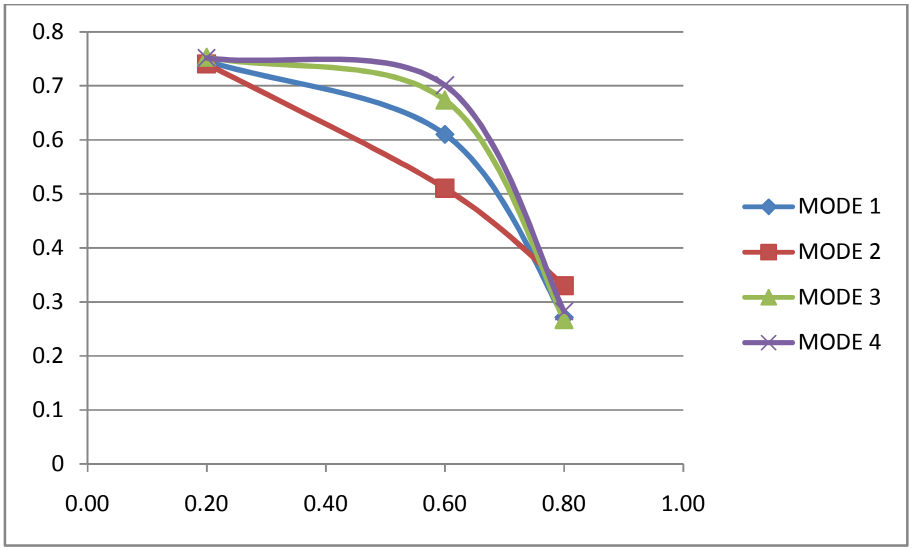
Experimental results for Multi crack Beam:

Beam Specification:

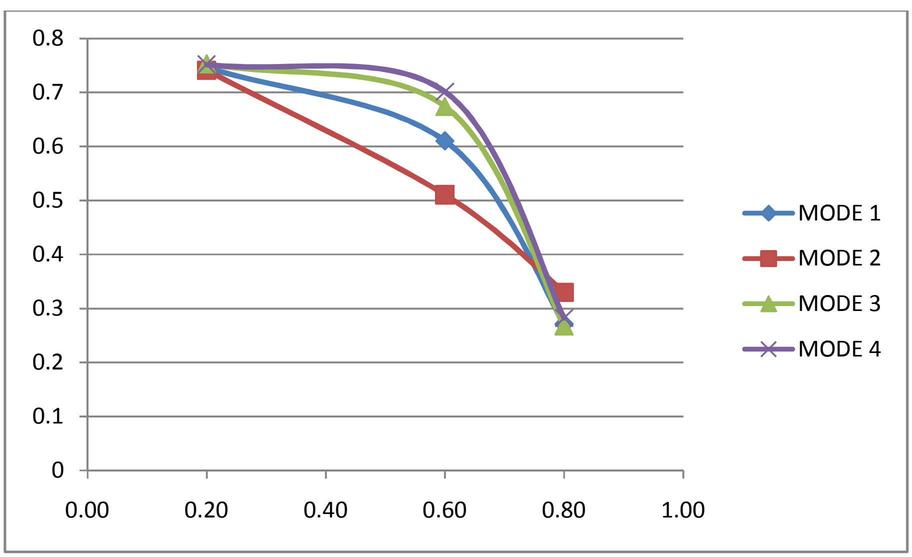
Length of the steel beam for free-free condition = 25 cm
Breadth = 9.2mm
Height = 9.2mm

S.no.		Crack depth	1st mode	2nd mode	3rd mode	4th mode
1	Cracks at 10mm, 5mm	2mm	144	928	2088	2792
2		6mm	136	887	2064	2744
3		8mm	48	560	1448	2744
4	Cracks at 7.5mm, 2.5mm	2mm	128	960	1936	2832
5		6mm	112	876	1720	2456
6		8mm	88	448	856	1736
7	No crack	nill	118	756	2125	4165

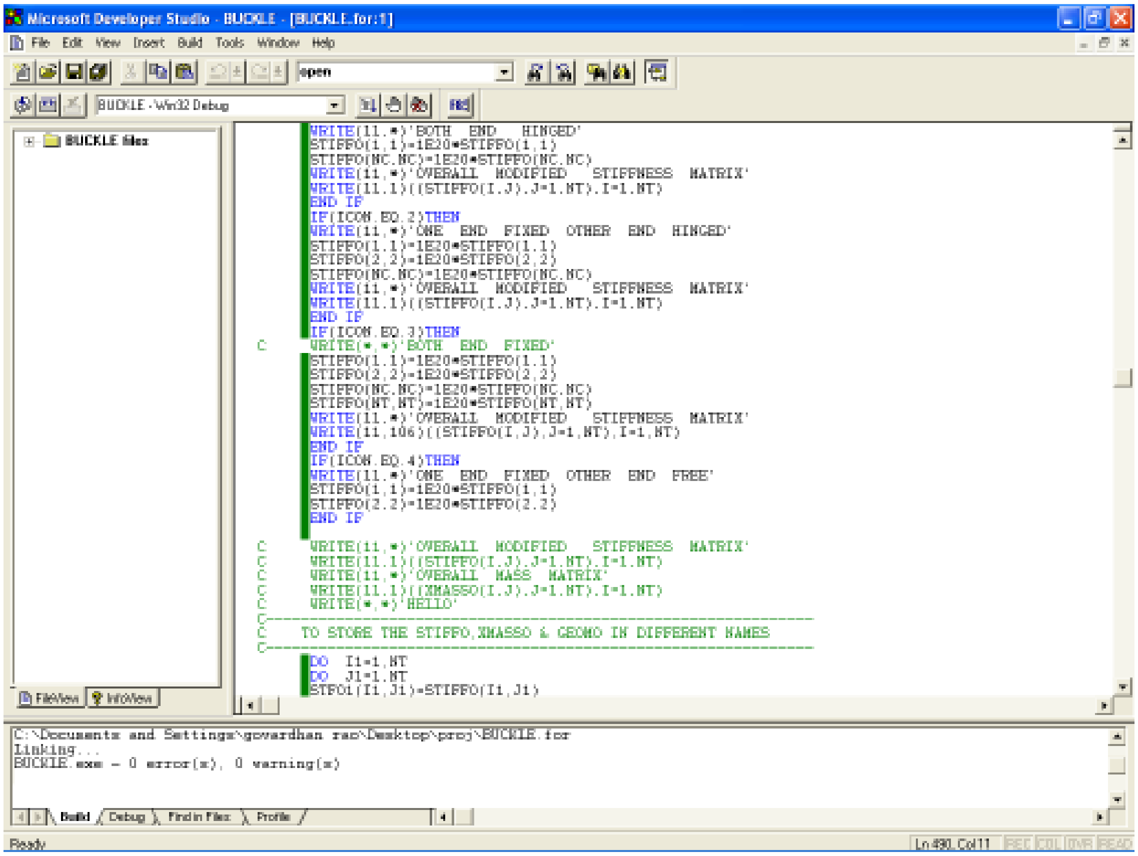
Cracks @ 0.4L , 5mm



Cracks @0.3L,2.5mm



Screenshot of the fortran program:



CONCLUSION

The vibration analysis of a structure holds a lot of significance in its designing and performance over a period of time.

In aluminium fixed-free condition it was seen that the results were in good coordinance with theoretical values. The lowest frequency was in 1^{st} mode. The frequency was increasing with each subsequent mode of vibration . The percentage of error was also decreasing as frequency is increasing.

The predicted values of natural frequencies and mode shapes for the specimens with a fatigue crack are close to those obtained experimentally. The verification of the analytical approach with a considerable amount of experimental data and with the results of other author's calculations showed that the analytical approach enables one to obtain well-founded relationships between different dynamic characteristics and crack parameters and to solve the inverse problem of damage diagnostics with sufficient accuracy for practical purposes.

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