FNITIE ELEMENT MODELING AND EXPERIMENTAL VALIDATION OF NON DESTRUCTIVE TESTING USING SURFACE RAYLEIGH WAVES IN ROLLING BODIES

THESIS

Waseem Anwar

Department of Aerospace and Mechanical Engineering

POLITECNICO DI TORINO

ITALY

Abstract

In this thesis the analysis of the characterization of surface and near surface defects is carried out using unconventional non destructive testing by using surface Ultrasonic Rayleigh waves .As Rayleigh waves are surfaces waves, they are mainly sensitive to surface and near surface defects and cause the surface particles to move in elliptical manner .Rayleigh waves are surface waves this feature makes these waves to investigate the complex geometries for defects characterization which are inaccessible by other form of waves since otherwise there will be multiple diffractions inside making it very complex. Ultrasonic testing using surface waves is a reliable technique for the inspection of rolling components i.e. ball bearings and other cylindrical bodies where greatest probability of defects lies on surface and sub-surface.

The existing Non Destructive Testing methods includes optical method, eddy current method and by measuring vibration of ball bearings. These methods are sensitive to surface defects. Since we know that in working condition failure starts at a point below the surface. It is of major interest to evaluate the subsurface defects if present.

About component like ball bearings measurements there are often multiple diffraction taking place within the specimen which makes conventional ultrasonic testing unreliable. The characterization procedures proposed in this thesis are therefore based on Rayleigh waves and Whispering gallery wave's .The penetration dept of these waves depends upon the mode selected, an appropriate mode should be selected to investigate the region of interest.

The near-field scattering of a Rayleigh wave at a crack on a spherical surface is studied theoretically and experimentally. FEM Package Abaqus 6.14 is used for the modeling of ultrasonic wave propagation. Material constitutive model used in simulations is stainless steel which is widely used for the production of ball bearings. The Explicit Dynamic analysis has been used and propagation of guided waves along the circumference and interaction in the presence

of the defect is implemented using finite central difference scheme. By comparing the simulations results and analyzing the time histories of the stresses and displacement of sphere undergoing mechanical waves , the present research investigate the detection of defects at surface and sub-surface using Rayleigh and Whispering gallery waves respectively.

There are different techniques used to investigate the presence of defects. One of the promising methods is time of flight. The method (TOF) technique is beneficial if the depth of the defect is larger than the wavelength of the incident acoustic wave. By analyzing the analytical results the time delay of the acoustic waves received at one of the equator is correlated with the depth of the crack.

On the other hand defects smaller than the wavelength can be evaluated by measuring and comparing displacement history of defected component with the non-defected. The characterization method introduced here to investigate the presence of defect is the attenuation in the displacement signal. The displacement at the equator is computed at different frequencies in ultrasonic range. Boundaries of the sphere are implemented as being stress-free. The transversal displacements are measured at the specific nodes of interest and the displacement histories are measured and compared at the surface of the specimen. Plots generated shows the comparison of wave signal monitored at sensor node. The defected signal shows the significant attenuation in magnitude and slow arrival time due to scattering around the defect.

The characterization procedures will be validated experimentally in future which consist of generations of Rayleigh waves by using YAG laser whose intensity will be modulated by acoustic optic modulator that shifts the light frequency for comparison purpose so in this way it will be possible to judge the path difference in terms wavelengths along with directional movement of the vibrating sphere. The components of vibrations will be measured by interferometric probe .By means of this technique there is no need of mechanical contact in order to investigate the mechanical characterization of solid free sphere.

Acknowledgements

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List of Symbols

c_g ……………………Group velocity (m/s)

c_L ……………………Longitudinal wave speed (m/s)

c_p ……………………Phase velocity (m/s)

c_T ……………………Transverse wave speed (m/s)

b..................................semi-width of contact length

d ……………………Diameter of sphere (mm)

E ……………………Young's Modulus, Elastic Modulus (kg m^{-1} s^{-2})

f ……………………Frequency (Hz)

G ……………………Shear Modulus (kg m^{-1} s^{-2})

k ……………………wave number

L ……………………Element edge length (m)

t ……………………Time (sec)

T ……………………Period (sec)

Δt ……………………Step time (*sec*)

u_i ……………………..Displacement vector ($u_x = u$, $u_y = v$, $u_z = w$)

x ……………………Cartesian coordinate (m)

y ……………………..Cartesian coordinate (m)

z ……………………Cartesian coordinate (m)

λ ……………………Wavelength (m)

μ ……………………Lame' constant

ν ……………………Poisson's ratio

ρ ……………………..Density (kg/m^3)

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Chapter 1 Introduction

1.1 Motivation

Surface defects present on steel ball bearings seriously affect the service life of bearings and stability of the bearing itself. Therefore a rapid and accurate inspection technique must be used in order identify defective steel balls which is of fundamental importance in the development of the ball bearings manufacturing companies.

The Ball bearing manufacturing companies are the most demanding and critical industry in terms of the material performance, the quality of manufactured ball, and how reliable are testing methods, specifically nondestructive testing methods. These days, steel materials have gained popularity because of its multiple advantages and use of it in critical components. This paper focuses on stainless steel material which are mainly used for the manufacturing of ball bearings and assembly sectors, particularly for the production of high precision bearings which require high rotation velocities or the ball bearings which work in extreme conditions[4]

1.2 Problem Statement

In the modern world, the ball bearings have been widely used and become an indispensable part in our industry. Non destructive techniques are mostly used to detect defects in material volume. For example; the steel pipelines are heavily used for the transportation of oil, natural gas even fresh water. The steel plates are often employed for structural and construction applications, such as buildings, bridges and vehicles. However, these structures are easily affected by environmental surroundings, such as mechanical wear or chemical corrosion for their material properties, thereby weakening their performance and reducing their service life. It is therefore necessary to find out an accurate system of analysis and diagnosis to regularly inspect these structures for structural integrity.

In order to improve the steel structural members' performance and reduce the operational cost at the same time, some new kinds of structure health monitoring (SHM) systems have been explored recently by many researchers. One idea of such SHM systems is to employ the ultrasonic Rayleigh waves to monitor the conditions of the product on production line. This is because the Rayleigh wave testing can offer many advantages that it is low in cost, higher efficiency and can monitor larger area of the structures. However, there are some limitation on its application, including the dispersive nature of the waves and the signal processing. Therefore, in out thesis the non destructive techniques for ball bearings using the finite element analysis producers to simulate the Rayleigh waves in steel sphere is significant for providing design guides for such non destructive ultrasonic system.

For the ball bearings, the creation of defect can take place at any stage of manufacturing process, and fall into two major classes: ''fissure'' defects (e.g. cracks, fissures, C-cracks, or grooves), and defects due to material (e.g. changes in elasticity, presence of micro-inclusions homogeneity of material used) generating undesirable variations in the properties of the material near the surface of ball bearings which is of major interest. For quality assurance of these balls, potential defects which can arise during the working condition in the finished products must be detected in a non-destructive manner before dispatching to our customers in order to gain the confidence of our existing and potential customers.

As we know and is shown in the Fig 1.1, surface and near-surface defects in steel balls can have more severe consequences than similar defects present away from the surface of so, the testing method we need to develop should be particularly well designed to analyze the sub-surface layer at a depth in microns. Experimental evidence shows that failure starts at a point below the surface. It is then of interest to determine sub surfaces defects .In Fig 1.1 the stress distribution on rolling bearings is presented where maximum stress lies at a depth of 0.78b where b is the semi-width of contact length.

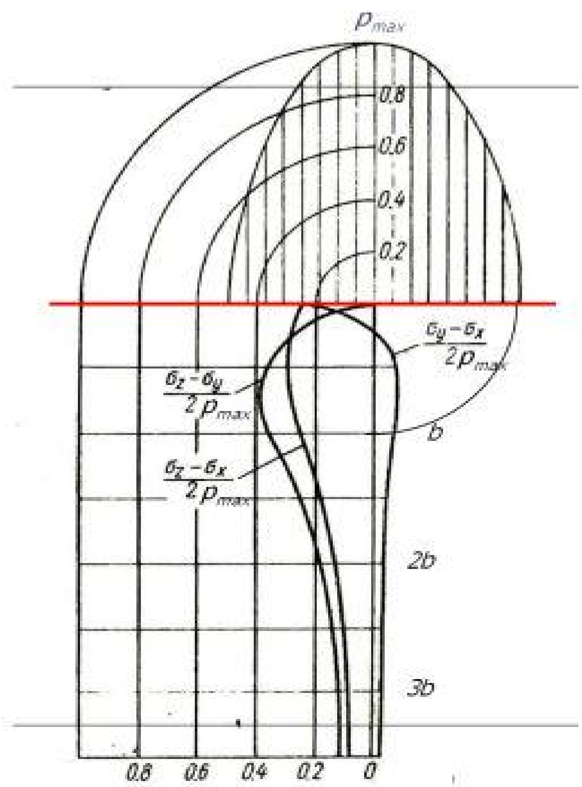

Fig1.1: Maximum Subsurface Stress [19]

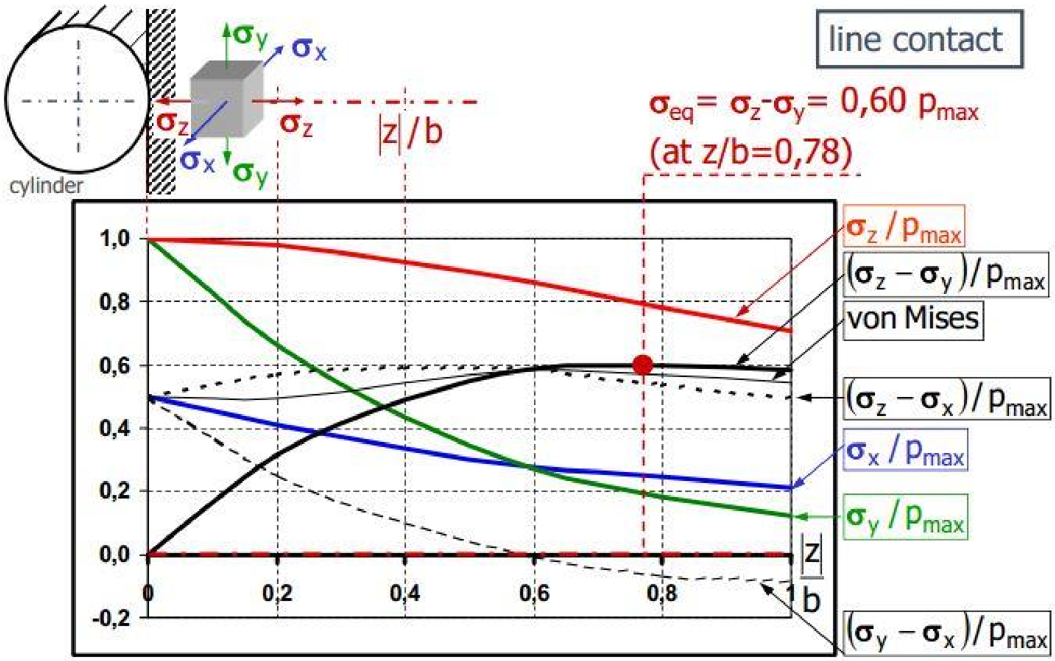

Fig:1.2 Maximum Subsurface Stress[19]

In thesis work we used a theoretical study of the elastic vibrations of balls to investigate the ball quality and the characterization of ball spheres. While performing experiments in future we will use both an ultrasonic probe (piezoelectric transducer) and a heterodyne optical probe which works on principle of interferometry, by taking the measurements for a large range of resonance frequencies.. If Ultrasonic probe is used for the generation of Rayleigh waves we can design the probe to support and generate the Rayleigh waves so that measurements can be taken without rotating the.

Unfortunately, the existing systems are well defined and reliable for the surface analysis, which mainly consist of optical methods or eddy-current methods but these methods are unable to locate the hidden defects present under the surface of ball, so Ultrasonic waves are the only feasible source that we can use in order to find out the conditions under the surface of sphere. In fact, these systems are generally capable to detect defects over one millimeter and any-thing under that cannot be detected.

In this thesis work is we investigate an ultrasonic resonance inspection technique that is appropriate option for detection of small dimensions components like steel balls by using the surface Rayleigh waves. A wide range of frequencies were chosen to investigate the depth of interest. Use of high frequencies Rayleigh waves allowed us to control the sub-surface areas of the ball by evaluating the vibrations components. But before going into details it is necessary to review the already existing methods used to identify the defects discussed in Chapter 2.

1.3 Research Objective

The objective of this thesis is to determine Rayleigh wave responses using ABAQUS CAE (a Finite Element Analysis (FEA) program). These FEA analytical results will be then compared to experimental results under the same conditions in order to detect the presence of defects on the surface or sub surface of ball bearings.

Simulations of tests using specimen are conducted at different resonance excitation frequencies. From the results of Abaqus simulations, response signal collected at the opposite pole of excitation is recorded and the response signal's waveform and propagation speed are analyzed in order to investigate the presence the defect at sub-surface level.

1.4 Outline of the thesis:

Chapter 2 is review of literature, which gives all the research backgrounds and useful information about this thesis. In this chapter structural health monitoring is introduced along with the different non destructive testing used in general.

Existing non destructive techniques are discussed in this chapter which are already in use to locate the presence of defects in ball bearings are discussed and need of using non destructive testing using Rayleigh waves is discussed .

After selecting guided Rayleigh wave testing as a primary technique, this chapter also outlines some vital knowledge which will be used in the Chapter 3 for the FEM simulations. For instance, the general knowledge and discussion about the piezoelectric sensors/actuators, different types and comparison with the Laser ultrasonic, guided wave types, wave mode selections and signal processing.

In Chapter 3, the elastic wave propagation in steel plates is simulated and analyzed and by using Abaqus software. Explicit Dynamic Analysis (EDA) applied in the FE model. Some vital parameters are discussed which are used to get simulations results. Furthermore, results are compared and analyzed between the perfect sphere and the defected sphere having a hole defect of diameter 20microns present at depth of 200 micron from the surface.

In Chapter 4, conclusions and results are discussed considering only the theoretical aspect of Guided Rayleigh waves and results are summarized and recommendations are given to suggest potential work.

The works presented in Chapter 5 focuses on the experimental validation of non destructive testing and comparison of the results which will take place in future. Besides, the relationship of the interaction between the defects and the elastic wave propagations in solid sphere are identified based on the numerical analysis.

Chapter 2 LITERATURE REVIEW

2.1 Introduction:

This chapter covers a brief review of the literatures on different Non Destructive techniques, using Rayleigh waves, and current research on Rayleigh wave inspection techniques. In addition, the signal operation and processing for Rayleigh wave analysis are also given in this chapter

2.2 The NDT approach

The development of nondestructive testing methods was motivated by a need to inspect engineering components subjected to heavy loading, fatigue and corrosion in order to prevent failure. Some NDT techniques do impair the properties and the performance of the component to be inspected and therefore, allow for the characterization of material properties like the elasticity, homogeneity and inspections of safety relevant components at pre defined interval of time during service to ensure that they meet the expectations and to ensure the reliability of the components for the future use .

The NDT techniques can be roughly classified in in five categories: [11]

- Visual inspection methods(penetrant liquid testing)
- Radiographic methods(X-radiography, gamma radiography)
- Acoustical and vibrational methods(ultrasonic testing and imaging)
- Electrical and optical methods(eddy current, magnetic particle inspection, potential drop)
- Thermal methods

2.3 Most Conventional Existing methods for Ball Bearings to find the defects:

As discussed,sub-surface defects present on steel ball bearings seriously affect the stability of the ball bearings and service life of the bearing itself. To accurately inspect and identify defective steel balls is of major importance in development of the bearing industry.

Currently the Aviko machines operating in the industry (Sorting Solutions Ltd., Bílina, Czech Republic) uses a combination of three techniques vibration, photoelectric, and eddy current sensors to investigate the presence of defects but all these methods are sensitive to surface defects only and are explained below. [15]

2.3.1 OPTICAL METHOD:

The optical method is designed for detecting visible defects, especially dirt and technological defects (crashes, overwhelms, flats, non-lapped spots etc) which can be seen on the surface. If the defect is detected by optical method and it is not detected by an eddy current method it is mostly a repairable defect, in this case ball must be cleaned again and checked through the optical probe.

The optical method evaluates the signal coming from the optical probe which illuminates a defined area of the surface of ball and measures the quantity of light that was reflected from that area. The source of light is semiconductor laser emitting in the visible spectrum of light (the area on the ball can be seen and it has a red color).

2.3.2 Eddy Current Method:

The eddy current method is specially designed for detecting the defects hidden under the ball surface, typically cracks, which may not extend all the way to the surface, or they or so well polished out of surface that, that the optical method cannot detect them. In general, these defects are always non-repairable defects.

2.3.3 Measurement of Vibrations Method:

This method specifies a detection of shape defects of ball by measurement of vibrations which are generated by the ball in the monitoring point, which could affect the meridian system. The method also ensures a good condition of the ball scanner mechanics because the condition of bearings, spherocone roller and drive disk has indirect influence on level of vibrations.

2.4 Active and Passive Ultrasonic Testing:

There are two types of Ultrasonic measurement techniques, they includes active and passive techniques. An active technique uses sensors to investigate the structure in order to detect the presence of defect and its quantitative description. Active sensors have a directed interaction with the structure and find out the reliability of the structure. On other hand, passive technique infers the state of the structure using passive sensors that are monitored over a period of time and fed back into a structural model. [1]

Passive testing listens to the structure but does not interact with it. In this thesis, the active SHM technique is used [2]. The actuator is used to excite the structure while a sensor placed at the opposite side of excitation source is used to monitor and collect the response in an effort to provide knowledge of its condition.

2.5 Vibration Approach versus Wave Propagation Approach

Location and nature of the defect in the structure can be determined by using Vibration approach by the detection of difference in the dynamical behavior of the structure. In presence of defects the frequency response functions (FRF) of structure change accordingly and indicates the presence of defects. However, if the dimension of defects is very low compared with the structure, it is difficult to distinguish the differences in the vibration response since the defects are relatively very small, sometimes the differences may be below the noise level [7]. However, there are some techniques that have been developed to amplify the differences and eliminate noise, effectiveness of using the vibration approach in detecting small defects in complex structures remains uncertain at present. However, the vibration approach is mainly useful for investigation of defects that are widespread or extensive in nature.

The conventional NDT methodology that has been used to detect and characterize the damage in the wave propagation approach. Comparing with the vibration approach, this approach is useful in detecting and characterizing the small and hidden defect since the wavelength is mostly smaller than the dimensions of defects.

In this thesis we used both approaches either by simulating the measure of normal vibration components and the velocity of the Rayleigh waves. Velocity estimation is mostly performed in order to verify the material properties of the elastic sphere since the velocity of the waves depends upon the material properties besides the frequency in case of the dispersive waves in which velocity depends upon frequency.

2.6 Pitch-Catch and Pulse-Echo Techniques

Ultrasonic non destructive testing methods are based on the propagation of elastic waves inside the material with an assumption that in case of damages the elastic waves alters its behavior .Mainly ultrasonic methods includes pitch catch and pulse echo techniques .

In case of pitch-catch method, ultrasonic actuators are used to generate the elastic waves at one location on the structure, and the response is recorded using a sensing transducer at a different point.

By examining the response the damage can be detected. By analyzing the wave attenuation the severity and location of the defect can be estimated.In order to find out the exact position of damage, various pairs of these transducers may be required.

In case of pulse-echo method, the transducer which is generating the elastic waves is itself responsible for the response measurement after the transducer has finished exciting the structure. In this case by investigating the echoes in the measured response due to wave reflections from the defect are measured in order to characterize the defect. However this method is mainly used where bulk waves are used to detect the material. In this scenario time of flight (TOF) can be used to locate the damage and the severity of the damage can be accessed from the amplitude of the reflected signal.

2.7 Piezoelectric Transducer

2.7.1 Introduction

In the past decade, a huge interest was seen in the field of sensors which generates ultrasonic waves specially Rayleigh waves. Rayleigh waves can be excited in structure and detected by different methods by sing piezoelectric transducer or laser ultrasonic. Using piezoelectricity most well is the wedge method which works in principle of converting bulks waves into Rayleigh waves. These conventional ultrasonic NDE techniques, wedge, or comb transducers, have three disadvantages (i.e., They have weak coupling with the structure through a fluid, they are resonant narrowband devices by themselves, and they excite and sense the response indirectly. So that these contact methods shows large variability which arises due to coupling variability of due to the surface roughness or due to concavity of the material. The response measured at the sensor is significantly affected by the change in the contact position. Because of all these reasons non contact generation and detection techniques are very attractive in non destructive testing. The major advantage of the non-contact techniques lies in the elimination of the coupling materials, which is undesirable or impossible in applications such as the testing of hot metals, or structures where the surface contamination produced by a coupling fluid cannot be tolerated.There is a benefit in using laser ultrasonic is that there is no need of contact for the propagation of elastic waves also the surface can be scanned easily and rapidly .The disadvantage with this technique is that its expensive and mainly used in the laboratories. For this reason, piezoelectric transducers are the most utilized for Rayleigh wave's excitations.

When transducers are attached to a test specimen for SHM, a transducer that sends out a wave is commonly referred to as an actuator, while a transducer that receives a wave is referred to as a sensor. The radial displacement deforms the sensor by creating elastic strain which propagates through a material. A gain property is responsible to relate the strain to voltage, thus the resulting compression and expansion of the sensor is translated in form of voltage and by comparing the different voltage level we will be able to differentiate between the defected and non defected spheres.

2.7.2 Piezoelectric transducer for Generation of Rayleigh waves:

As discussed in section, Rayleigh waves can be generated by using piezoelectric contact transducers or by using optical techniques.

A contact transducer is attached to the surface of the specimen, usually attached with the help of a coupling e.g. oil to transmit the acoustic signal into the sphere. But the use of coupling oil cause many drawbacks within generation and detection procedures. Insufficient amount of couplet results in dry area thus cause inadequate couple surface area on other hand excessive amount of couplet results in losses of the resonance signal. Different piezoelectric transducers are used to generate Rayleigh waves which include Angle beam wedge transducer, comb transducers and inter digital transducer but mostly wedge transducer and delay line transducers are used.[5]

2.7.3 Types of transducers used for generation of Rayleigh waves:

There are different types to produce the Rayleigh waves by using the piezoelectric transducer, but mainly there are two which are explained below.

2.7.3.1 Wedge type transducers

For generation of Rayleigh waves using wedge transducer, a longitudinal bulk wave transducer is placed with a certain angle on a wedge of low speed material. This way of generating Raleigh waves is very simple and cheap; the only difficulty in case of ball bearings is design a transducer which can support the ball in such a way that there should be single point of contact where Rayleigh waves can be excited. In case of wedge transducers waves should be generated and detected very precisely since there is some amount of leaky Rayleigh waves.[3]

2.7.3.2 Delay line Transducer

These devices are ideal for thin material testing, where it is important to separate the excitation pulse recovery from back wall echoes. A delay line can also be used as a thermal insulator, protecting the heat-sensitive transducer element from direct contact with hot test pieces, and delay lines can also be shaped or contoured to improve sound coupling into sharply curved or confined spaces. In case of ball bearings tests delay line transducer is mainly used in concave shape which can generate the waves and support the ball bearings simultaneously.

2.8 Laser Ultrasonic:

Lasers can be used for generation and detection of ultrasound, mostly YAG laser is used for the generation of ultrasonic waves and the laser detection methods like the Michelson interferometer are well known measurement procedures for acoustic waves and vibrations. Laser generation methods were first applied by White in the 1960s.In the last two decades application of laser excitation is increased due to its advantages however huge cost is the main factor which restricts the use of laser techniques.[14]

A laser emits electromagnetic radiation with a frequency spectrum of between less than 104 Hz (long radio waves) and 1021 Hz (high energy gamma waves), and a propagation velocity of

$$c = 2.9979 \times 10^{8}\ \text{m/s} \qquad 2.1$$

A monochromatic electromagnetic radiation in the wavelength range of 200 nm to 10 μm, is used for the purpose of the detection of defects, any change in the normal component of vibrations will cause the Doppler frequency to change and converts the displacement in form of Doppler fringes, for one Doppler shift the displacement will be half of the wavelength of laser beam.In this way by counting the number of the constructive or destructive fringes we can perform quantitative analysis of vibration in terms of displacement and voltages and we can differentiate between the undefected and defected spheres

2.9 Elastic Waves

In the field of non destructive testing elastic waves are primary methods for the detection of defects .These waves are generated as a result of restoring forces between particles when the material is displaced elastically. These elastic waves can transmit and detect the changes in the velocity inside the material.[6] The change in the velocity influences the quantitative wave characteristics including the frequency, wave speed, wavelength, wave velocity, wave number, and amplitude of displacement.

There are two types of Elastic waves which consist of either guided waves or bulk waves. Bulk waves travel inside the material away from the boundaries and there exist a finite number of modes. However, Rayleigh waves travel near the surface of a test specimen or through the thickness in case of thin materials and named as Lamb waves which usually propagates on the surface and exhibit infinite number of modes because guided waves are dispersive in nature. In real life, there is no physical material that doesn't have boundary conditions. Therefore, to investigate the surface of ball bearings Rayleigh waves are considered as the best option.

Coupling between longitudinal and vertical shear waves that are reflected and refracted at the free surfaces of a material generates and these Rayleigh waves are free waves on the surface of a semi-infinite solid. The traction forces vanish on the surface and the amplitude of the wave is dependent on the depth and decays into the depth of the solid. Lamb waves are plain strain that occur in a free plate. The traction forces vanish on both the upper and lower surfaces of the plate. Because of these different characteristics, Rayleigh waves are useful for damage detection of surface cracks in thick structures like ball bearings and Lamb waves are useful for damage detection in plate and shell structures.[9]

2.9.1 Rayleigh Waves:

Rayleigh wave is a type of surface acoustic wave that travel along the surface of solid material. They can be generated in materials in different ways, by a localized impact or by using piezo-electric transduction, and are frequently used in non-destructive testing for detection of surface and sub-surface defects.

The existence of Rayleigh waves was predicted in 1885 by Lord Rayleigh, after whom they were named. At the surface and at shallow depths the motion retrograde itself, at greater depths the particle motion becomes prograde. In addition, the amplitude of Rayleigh waves decreases as the depth into the material increase. The depth of significant displacement in the solid material is almost equal to one acoustic wavelength. Rayleigh waves are different from other types of surface or guided acoustic waves such as Love waves or Lamb waves, both being types of guided waves supported by a layer, or longitudinal and shear waves, that travel in the bulk.

Since Rayleigh waves are confined near the surface, their in-plane amplitude when generated by a point source decays only as **$1/\sqrt{r}$ where"r"** is the radial distance. Surface waves therefore decay more slowly with distance than do bulk waves, which spread out in three dimensions from a point source because of this nature the Rayleigh waves can travel more distance than the bulk wave which is of major importance in non destructive testing.

2.9.2 Rayleigh waves in Non Destructive Testing:

Rayleigh waves are widely used for materials characterization, to discover the mechanical and structural properties of the object being tested – like the presence of cracking, and the related the properties of different materials by analyzing the velocity of Rayleigh waves in solid materials . This is in common with other types of surface waves. The Rayleigh waves used for this purpose are in the ultrasonic frequency range.

They are used at different length scales because they are easily generated and detected on the free surface of solid objects. Since they are confined near the surface of the free surface within a depth equal to the wavelength, linked to the frequency of the wave, different frequencies can be used for characterization at different depth scales.

2.9.3 Rayleigh waves Propagation on a Sphere :

Conversely the Rayleigh waves propagation on the plane surface is different from the Rayleigh waves propagation on the Spherical surface .The propagation of the surface acoustic waves having frequency “f” and wave number “k” on a sphere of radius “a” is dispersive in nature .In this thesis work the vibrations having non zero radial displacements are considered .The resonance frequencies of spheroidal vibration can be derived using Helmholtz equation and the results were derived by the researcher D Royer and Y.shui, they already calculated the normalized graph for the resonance frequencies of sphere of radius “a” [10]

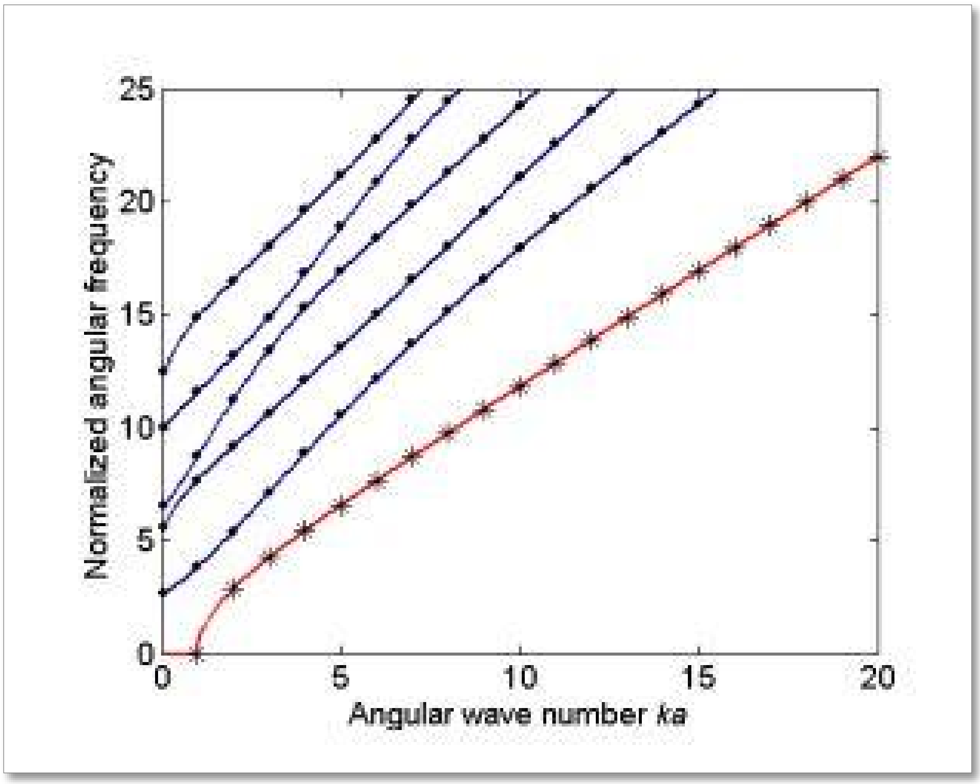

Fig 2.1: Normalized curves for angular resonance frequencies[10]

2.9.4 Velocities of Rayleigh waves:

The velocities of waves can be defined in many different ways. Generally speaking, the Rayleigh wave velocities can be classified into the group velocity and phase velocity. The group velocity is the velocity with which wave packets travel. In contrast, the phase velocity is the wave speed of the individual waves. Fig. 2-9 shows the detailed information about the phase velocity and group velocity. More precisely, the velocity of wave train in contrast with that of the carrier is the phase velocity. The velocity of the envelope is the group velocity.

The group velocity v_g is the speed of the overall shape of a modulated wave (called the envelope). This is defined by $d\omega/dk$ where ω is the angular velocity and k is the wave number. The phase velocity v_p of a wave is the speed at which a given phase of a wave travels through space, equal to ω/k.

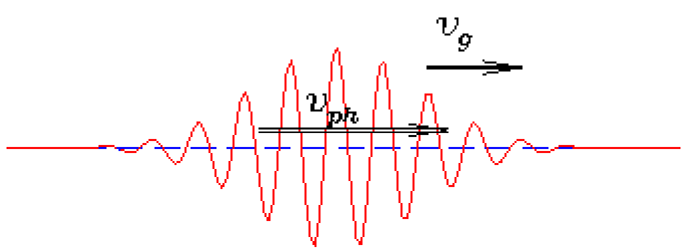

Fig2.2: Phase vs. Group velocity

2.9.5 Rayleigh waves Dispersion in Sphere:

In Fig. 1, the normalized angular frequency $\frac{\omega a}{VR}$ plotted versus the angular wave number *ka*. Integer values *n* of *ka* reflect a resonance condition, for example *n* = 0 implies a longitudinal wave radial resonance. For *n* ≥ 1, we consider only the lowest solution ω*n* corresponding to a mechanical disturbance localized near the surface that becomes a Rayleigh wave on a plane surface as *n* → ∞ .[12] The other solutions called whispering gallery modes, have displacements more concentrated in the sphere . As *n* approaches one, the frequency and then the phase velocity of the Rayleigh mode vanishes. After the impact of the laser pulse on the surface, the Rayleigh wave continues propagating as an elastic disturbance around the sphere or the cylinder. The number of turns is only limited by attenuation, dispersion and diffraction effects .

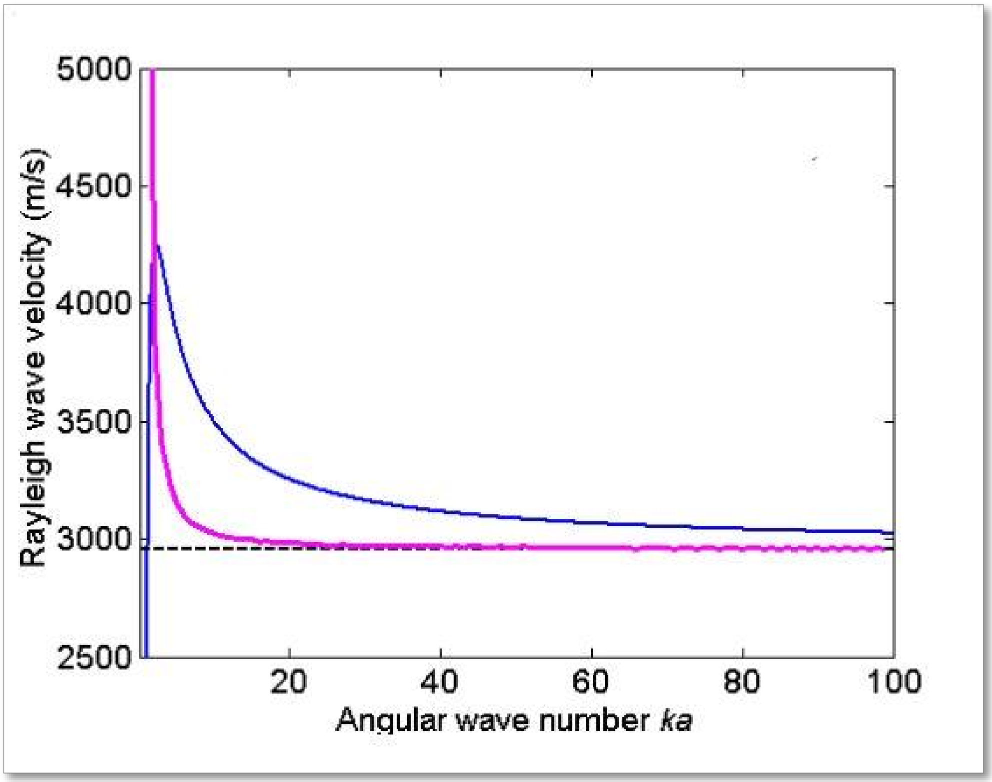

Fig 2.3 : Phase(in blue) and group velocity(in pink) dispersion curve of Rayleigh waves propagating on a steel sphere.[12]

This similitude allows us to forecast that the dispersion characteristic does not depend significantly on the type of the resonator either it's a sphere or cylinder and on the elastic properties of the constitutive material. Approximation of the phase velocity dispersion curve has been deduced from the matching conditions on the phase ϕ of the Rayleigh wave. The solution of the wave equation depends on the angular coordinate θ according to the law e^{ika} . After each circum-navigation along the meridian, if the phase variation $\Delta\phi = 2\pi\, ka$ equals an integer for a sphere, a constructive interference occurs

$$\phi_S = (n + 1)\, 2\pi \qquad 2.2$$

The difference between the wave number K_n and K_{n+1} is constant and is given as

$$\Delta k = K_{n+1} - k_{n=} 1/a \qquad 2.3$$

From the formula $\Delta\omega = 2\pi(fn_{+1} - f_n)$, the ratio can be written as

$$\Delta\omega/\Delta k = 2\pi a\,(\Delta f)_n \qquad 2.4$$

The above equation gives us the group velocity of the mode n only from the frequency difference $\Delta f = (fn_{+1} - f_{n)}$.[12]But this equation is only valid for a higher value of n where the difference in frequency between the two peak values remain constant,this constant difference is termed as “Frequency Step”

For larger values of n=ka, the frequency step remains constant, so we can write from the equation 2.4.that the group velocity remains constant irrespective of the value of n and the group velocity approaches the value of V_R.

$$V_R = 2\pi a\Delta f \qquad 2.5$$

The above expression is only true at very high value of n, otherwise at low n value of ka, we see the dispersion phenomena and above expression in not valid.

As definition of Group velocity V_g

$$Vg = d(\omega a)/d(ka) = V_R \quad \text{For } ka >> 10 \qquad 2.6$$

By integrating the above expression, we can get a linear relationship between the Normalized angular frequency and the angular wave number ka, and can be written as

$$\frac{\boldsymbol{\omega}\ \mathbf{a}}{\boldsymbol{VR}} = ka + \varepsilon 1 \qquad 2.7$$

As shown in Fig.4, the dimensionless coefficient ε1 computed for a sphere , depends only on the material Poisson’s ratio υ.[300] Since $V_R = 2\pi a\Delta f$, and for a Rayleigh mode of large order $n = ka$, Eq. 6 can be written as

$$m = n + \varepsilon 1 \qquad 2.8$$

where m is the ratio between the resonance frequency f_n and the frequency step Δf. In the case of a sphere, an empirical relation, where m is also an integer: $m = n + 2$, was proposed by Hsieh [16]. Fig. 4(a) shows that the difference $m - n = \varepsilon 1$ is not a constant equal to 2. It increases from 1.99 to 2.63 as the Poisson's ratio varies in the usual material range ($0 \le v \le 0.5$)

The corresponding asymptotic behavior for the phase velocity:

$$V = V_R\,(1 + \varepsilon 1/ka) \qquad 2.9$$

In order to improve the approximation, we introduce a second term in Eq. 8:

$$V = V_R\,(1 + \varepsilon_1/ka - \varepsilon_2/k^2a^2) \qquad 2.10$$

Like ε1, the dimensionless coefficient ε2 depends only on the material Poisson's ratio .This expression leads to a correction of the second order for the Rayleigh wave group velocity:

$$V_g = V_R\,(1 + \varepsilon_2/\, k^2a^2) \qquad 2.12$$

The second coefficient ε2 can be determined from characteristic points in the low frequency range of the velocity dispersion curve.

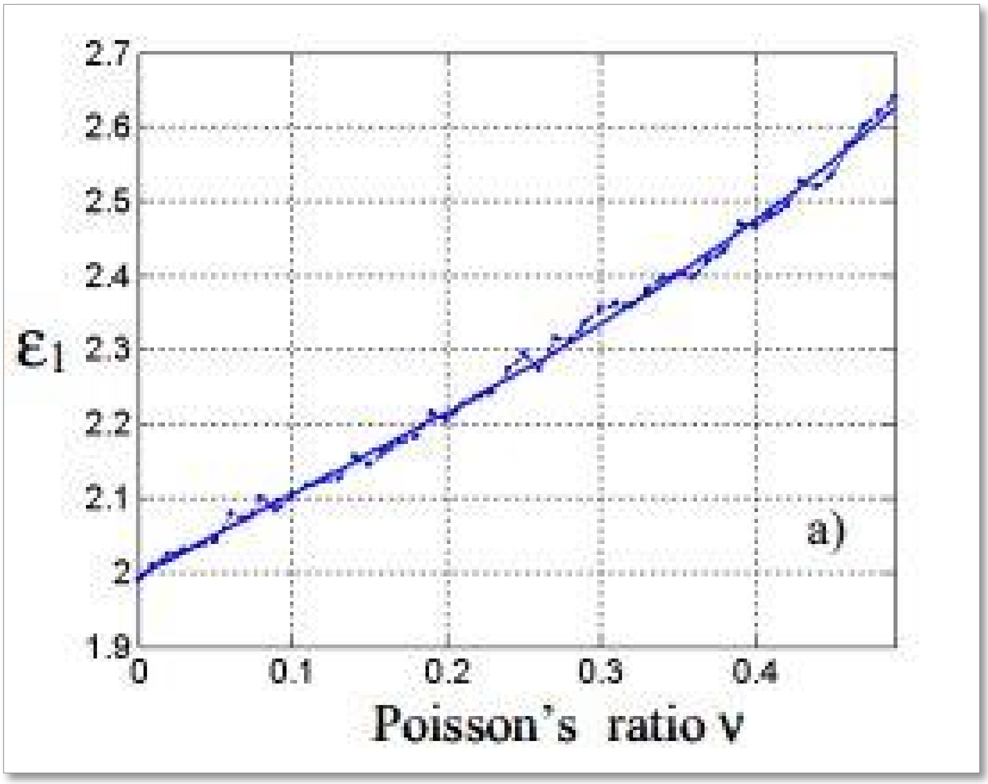

Figure 2.4. Variations of the coefficients ε1 versus the Poisson's ratio v for Rayleigh waves propagating on sphere

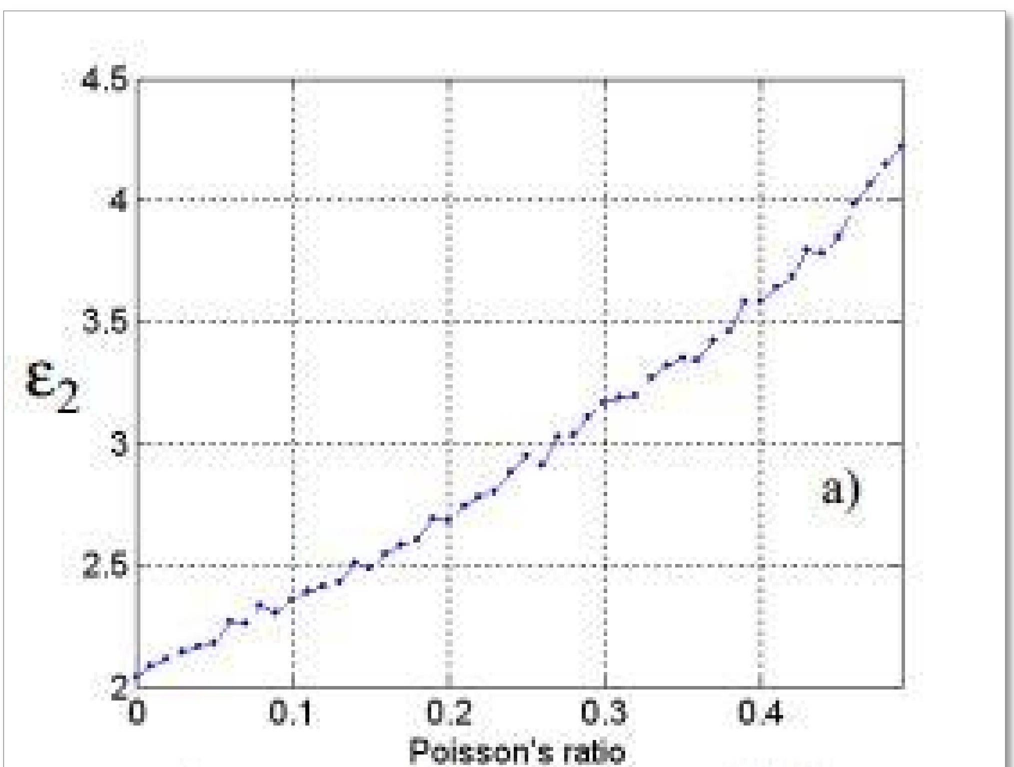

Figure 2.5. Variations of the coefficients ε2 versus the Poisson's ratio ν for Rayleigh waves propagating on a sphere

2.9.6 Resonance frequencies for Sphere:

The resonances of an elastic sphere have been studied in geophysics and acoustics since a long time In seismology, a homogeneous sphere is the simplest model of the earth. In mechanical industries ball bearings are the heart of many machines; these steel spheres are usually excited by acoustic wave's incident from the Rayleigh wave sources. At high frequencies, vibrations involving a radial displacement component resemble surface acoustic waves (SAW), in that the wavelength is small compared to the radius. The vibration is localized in the cortical zone of the curved surface, penetrating the material to depths of approximately one wavelength.

Normalized curve of the natural frequencies of steel spheres are already calculated by researcher Daniel ROYER and Dominique CLORENNEC, [12]as shown in the Fig 2.1.Rayleigh wave mode and whispering gallery modes are shown in the fig , the penetration depth of each mode is different and depends upon the depth of surface to be investigated.As we move towards higher value of n, the cortical zone of the ball sphere become more sensitive and even minor defects can be calculated at higher value of n,on the other hand whispering modes are effected when we are interested towards the center of ball sphere.

The resonance frequencies for the sphere can be calculated from the normalized curve for a sphere diameter of 33 mm as shown in the Fig 2.6

Since the maximum stress lies below the surface so we are using the Rayleigh mode at higher frequencies in order to investigate the surface/sub-surface defects. The Rayleigh mode natural frequencies are shown in the Fig below

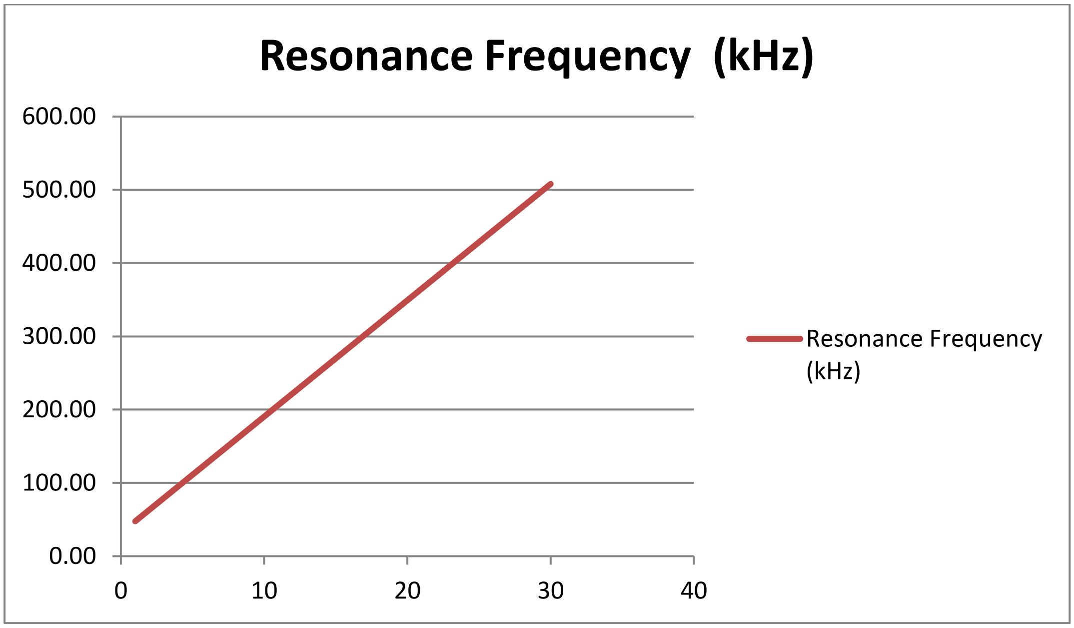

Fig2.6-Resonance frequencies of steel sphere –Diameter 33.3mm

2.9.7 Rayleigh waves in non-destructive testing:

Rayleigh waves are widely used for materials characterization, to discover the mechanical and structural properties of the object being tested – like the presence of cracking. This is in common with other types of surface waves. The Rayleigh waves used for this purpose are in the ultrasonic frequency range.

They are used at different length scales because they are easily generated and detected on the free surface of solid objects. Since they are confined in the vicinity of the free surface within a depth (the wavelength) linked to the frequency of the wave, different frequencies can be used for characterization of the defects at different depts.

2.9.8 Advantages and Disadvantages of Rayleigh Waves in Non Destructive Testing

Mostly bulk waves are used for conventional non destructive testing but these bulk waves works on basis of reflection and transmission coefficient which will not work in case of sphere due to multiple reflections, Rayleigh waves are particularly advantageous since these are surface waves and can travel long the surface layer and even cover complex geometries, which are not accessible by other form of waves

However, there are few disadvantages in using surface waves in NDT. These disadvantages are generally due to wave behavior i.e. Dispersive nature of Rayleigh waves. To analyze the response, these dispersive phenomena should be understood.[8] These characteristics are discussed in Chapter 2.

CHAPTER 3

MODEL DEVELOPMENT

3.1 Introduction:

A common objective of ultrasonic inspections is to detect, locate, size and characterize defects in ball bearings. The current range of ultrasonic is not suitable for analyzing the sub-surfaces. In this study ultrasonic Rayleigh waves are modeled numerically by using explicit finite difference method.

For the Non destructive tests, we use 33.3mm ball diameters made up of stainless steel alloy. Table 1 shows its dimensions and material properties. The Rayleigh waves are generated by a localized impact at one of the poles of steel ball and at the opposite pole the normal component of the vibrations is measured by means of an optic probe. Information related to the geometry defects of the ball bearings will be hidden inside that signal and characterization of defects can be made possible by analyzing the signal carefully.

3.2 Modeling of Specimen for Non Destructive Testing

As for the finite element modeling, the steel sphere was treated as a 3D deformable solid and meshed with C3D8R solid elements, which were chosen properly according to wave length.

The defects added to the sphere model are a hole of diameter 20 micron and depth 200 mm,. Those defects were designed to locate at different points of sphere at a depth of 200 microns.

The whole modeling and the vital parameters used in explicit analysis for FEM simulations are discussed in the next sections.

3.3 Modules in Abaqus CAE 6.14:

There are different modules which in listed and explained below in a hierarchal order.

3.3.1 Part Module:

There are several ways to create a part in Abaqus/CAE:[13]

- Create the part using the tools available in the Part module.
- Import the part from a file containing geometry stored in a third-party format.
- Import the part mesh from an output database.
- Import a meshed part from an Abaqus input file.
- Merge or cut part instances in the Assembly module.
- Create a meshed part in the Mesh module.

The Part module we followed in this thesis work is

- Part was created by using solid that define the geometry of the part.
- Sketcher was used to form the profile of a part's features. The profile was then revolved along the z-axis to create a solid 3D sphere.
- Defect of 20 micron at depth of 200 microns was inserted and part was regenerated.

3.3.2 The Property module

Property module is used to perform the following tasks:

- Define materials.
- Define section profiles.
- Define sections.

3.3.1 Defining materials

A material definition specifies all the property data relevant to a material. We specify a material definition by including a set of material behaviors, and supply the property data with each material behavior included . Material editor is used to specify all the information that defines each material

Each material that is created in Abaqus is assigned its own name and is independent of any particular section. Also Abaqus/CAE assigns the properties of a material to a region of a part when we assign a section referring to that material to the region.

3.3.2 Material Properties of stainless steel alloy.

The material used here is stainless steel and the mechanical properties which are used in simulation is listed in table below.

Steel	Value	Units
Diameter of sphere	33.3	mm
Density	7850	Kg/m^3
Modulus of Elasticity	$210x10^9$	N/m^2
Poisson Ratio	0.27	--

Table 3.1

3.3.3 Defining sections

Once the material properties are defined, then we defined a section containing all the information about the properties of a part or a region of a part. The information required in the definition of a section depends on the type of region in question. A rigid region requires a section that describes its mass properties.

When you assign a section to a part, Abaqus/CAE automatically assigns that section to each instance of the part. As a result, the elements that are created when we mesh those part instances will have the properties specified in that section.

Homogeneous solid sections are used here to define the section properties three-dimensional, and axisymmetric solid regions

3.3.4 Assigning a section

Once section is defined Abaqus CAE assigns section properties to a part by first creating a section and then selecting Assign Section to assign the section to a part; a region of a part, including its skins or stringers;[13] or a set of elements. Section properties that we assign to a part are assigned automatically to all instances of that part in the assembly. Abaqus/CAE after assignment the section turn the part into green color confirming that all material properties which we defined in the section are successfully done, or colors the region turin into yellow if there are overlapping section assignments.

3.4 The Step module

In this Step module we defined the type of analysis we need to perform which is Explicit Dynamic in our case. In thesis we used the Step module to perform the following tasks:[13]

- Create analysis steps.
- Specify output requests.
- Specify adaptive meshing.
- Specify analysis controls.

Within a model we defined the analysis steps which provide a convenient way to capture changes in the way parts of the model interact with each other, the removal or addition of parts, and any other changes that may occur in the model during the course of the analysis. In addition, steps allow us to change the analysis procedure, the data output, and various controls. we can also use steps to define linear perturbation analyses about nonlinear base states.

3.4.1 Output requests

Abaqus writes output from the analysis to the output database; we specify the output by creating output requests that are propagated to subsequent analysis steps. An output request defines which variables are needed to be extracted in analysis step, and at what rate they will be output. For example, while doing the simulation of ball bearing we requested output of the entire model's displacement field at the end of a step and also request the history of a normal component of displacement.

Similarly we can define the adaptive mesh regions and specify controls for adaptive meshing in those regions. There are mainly two types of steps

3.4.1.1The initial step

In Abaqus/CAE initial step has been created at the very start of analysis and creates only one initial step for a single model, and it is not possible to rename or delete it.

The initial step is necessary to define the boundary conditions and predefined fields that are applicable at the beginning of the analysis.

In our case we defined Step-1 which is our first analysis which is linear perturbation step.

3.4.1.2. Analysis steps

One or more steps are followed by the initial step. Each step associates itself with a specific procedure that defines the type of analysis to be performed. For example in our case we used the explicit dynamic analysis for the ultrasonic testing of ball bearings other may includes heat transfer analysis or static stress analysis. Analysis procedure can be change from step to step in a meaningful way so in Abaqus there is great extent of flexibility in performing the analysis During the analysis stress,displacements are updated throughout the analysis steps the previous history is always included in the new analysis step.

We can define as much analysis we need to perform but there is restriction about the sequence of steps.

3.4.3 Explicit dynamic analysis

We decided to select explicit dynamic procedure as it perform large number of small increments in a very efficient manner. For this analysis central-difference time integration rule is used. The dynamic equilibrium equations are satisfied by the explicit central-difference operator at the beginning of increment "t", at time *t* the accelerations calculated are used to advance the velocity solution to time $t + \Delta t/2$ and the displacement solution to time $t + \Delta t$

3.5.3.1 Some vital parameters used in explicit dynamic procedure

Two condition must be satisfied before modeling with Explicit Dynamic.In this study, these two conditions are described, analyzed and calculated as follows.[17]

3.5.3.2Determining maximal element size (L_{max}) of FE models

According to spatial sampling criteria, the maximal element size (L max) should be small enough, thereby allowing the smallest wavelength of the wave can exist in the computation domain. To determine the maximal element size, the following procedure should be considered.

In the first place, we need to calculate the transverse wave speed (CT) also it was calculated in the chapter 2nd

$$C_T = \sqrt{E/2\rho(1+\upsilon)} \qquad 3.1$$

where G is the shear modulus,μ is the Lame constants,ρ is the density, E is the Young's modulus and υ is Poisson's ratio.

According to Table 3.1 the transverse wave speed can be calculated as

$$C_T = \sqrt{E/2\rho(1+\upsilon)} = \sqrt{210\text{x}10^9\ \text{N/m}^2\ /\ 2\text{x}7850(1+0.27)} = 3290\ \text{m/sec} \qquad 3.2$$

The simulation has been performed at different resonance frequencies, which is discussed in Section 2.3. Then, applying this maximum frequency and the smallest wavelength (λmin)is calculated, as we are performing at different resonance frequencies so we need to calculate these vital parameters at each of the frequency.The Steps are listed below

- Interested resonance frequency (f_{max}) should be selected according to desired penetration depth of interest for Rayleigh signal.
- Smallest wavelength can be calculated from the maximum frequency defined in the step above, which is

  $\lambda_{min} = C_T / f_{max}$ 3.3

- From step 2 maximum element size can be calculated by using the following relation

  $L_{max} \leq \lambda_{min} / 100$ 3.4

For the simulation the maximum element size is calculated from above equation and can be used in the Mesh Module in Abaqus CAE

Hence, this value can be used in the Mesh Module in Abaqus/CAE

3.5.3.3 Calculating Time Step (*t*)

Because of the explicit process is using known values from the previous time step, the time step Δt is an important factor for the accuracy of the solution. Hence, it should be calculated before creating the analysis step in the modeling process. Generally, the accuracy of the model can be enhanced with increasingly smaller integration time step. It means if the time step (Δt) is too large, the high frequency components could not be resolved accurately. In contrast, if smaller time step (Δt)is used, the more calculation time could be wasted. Therefore, the suitable time should be found by the following processes In order to determine the time step(Δt), the Lame's constant(λ,μ)should be calculated firstly[16]

$\mu = E/2(1+\upsilon) = 210\text{x}10^9 / 2\text{x}(1+0.27)\ N/m^2 = 82.32\text{x}10^9\ )\ N/m^2$ 3.5

The other lame constant λ can be calculated as

$\lambda = E\,\upsilon/(1+\lambda)(1-2\,\upsilon) = (210\text{x}10^9\ \text{x}0.27)/(1+0.27)(1-2\text{x}0.2) = 97\text{x}10^9\ N/m^2$ 3.6

From the above calculated lame constants the longitudinal wave velocity can be calculated as

$$C_L=\sqrt{\lambda}+2\,\upsilon/\rho=5988 \text{ m/s} \qquad 3.7$$

The time step can be calculated as

$$\Delta T \leq L_{min}/c \qquad 3.8$$

The value calculated from the above equation can be used in step module.

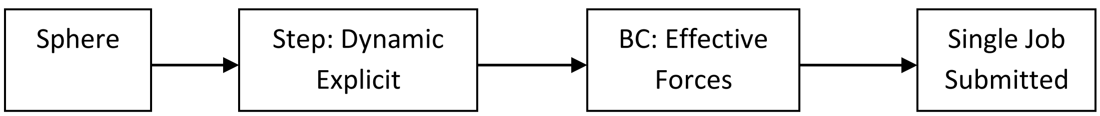

Fig 3.1-The flow tree of Abaqus Explicit Model

Parameters	Description
Diameter of Sphere	33mm
Frequency	It has been determined at the beginning of section
The Maximum Element Size	λ_{min} is the smallest wavelength L_{max} should be small enough, thereby allowing the smallest wavelength of the wave can exist in the computation domain
The Time Step	It can assure a good precision in calculating and analysis of component

The Total Time	This condition in to ensure the sensor can receive signal at least one time period

Table 3.2 The method of choosing parameters of FEM model

Parameters	Values
L_{max}	0.0001m
ΔT	8E-8sec
Time step	0.0001s
Frequency	Resonance frequencies

Table 3.2 Main parameters in explicit dynamic simulations the steel sphere

3.4.3.4 Time incrementation:

Time increment in the used in the explicit method should be small enough to satisfy the condition of stability limit of central difference operator. If this condition is not full filled the results obtained will be unstable and displacement measured at the opposite pole of ball sphere will oscillate with increasing amplitude with the passage of time. Time increment is calculated from the equation .

Time incrementation also depends upon the types of material assigned in the model, Since in our model we are using the only one material so our meshing depends upon on the smallest element of the mesh which is calculated in the section 3.4.3.4 and the time incrimination is done according to the standards.

3.5.3.5 Automatic time incrementation

The default time incrementation in Abaqus/Explicit is fully automatic and it requires no user intervention. Two types of estimates are used to determine the stability limit: element by element and global. An analysis always starts by using the element-by-element estimation method and may switch to the global estimation method under certain circumstances, as explained below.

3.5.3.6 Element-by-element estimation

In an analysis Abaqus/Explicit initially uses a stability limit based on the highest element frequency in the whole model. This estimation is determined using the current dilatational wave speed in each element.

The element-by-element estimate is conservative; it will give a smaller stable time increment than the true stability limit that is based upon the maximum frequency of the entire model. In general, constraints such as boundary conditions and kinematic contact have the effect of compressing the Eigen value spectrum, and the element-by-element estimates do not take this into account.

The concept of the stable time increment as the time required to propagate a dilatational wave across the smallest element dimension is useful for interpreting how the explicit procedure chooses the time increment when element-by-element stability estimation controls the time increment. As the step proceeds, the global stability estimate, if used, will make the time increment less sensitive to element size.

3.5.3.7 Global estimation

The stability limit will be determined by the global estimator as the step proceeds unless the element-by-element estimation method is specified, fixed time incrementation is specified, or one of the conditions explained below prevents the use of global estimation.

Abaqus/Explicit monitors the effectiveness of the global estimation algorithm. If the cost for computing the global time estimate is more than its benefit, the code will turn off the global estimation algorithm and simply use the element-by-element estimates to save computation time.

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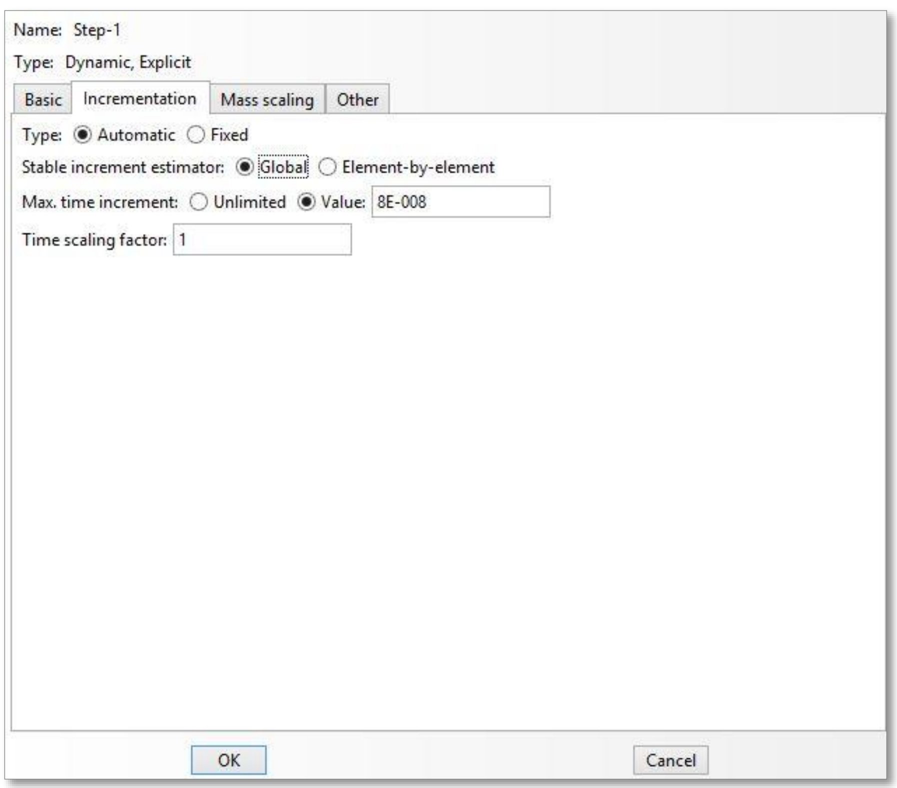


Fig: 3.2 Global Stable increment estimators

3.5.3.8 Advantages of the explicit method

An explicit dynamics analysis is used to determine the dynamic response of a structure due to wave propagation, impact or rapidly changing time-dependent loads and this procedure is ideally suited for analyzing high-speed dynamic events. The results in an explicit dynamics analysis are not automatically checked for accuracy as they are in Abaqus/Standard (Abaqus/Standard uses the half-increment residual). But in majority of the cases this is of no importance because the stability condition defined above is imposes a very small time increment so that if any case solution changes the change in solution is negligible , which makes the incremental calculations very simple. Besides it explicit analysis usually takes large number of increments so this method is very attractive for the problems where dynamic response time is few orders longer than the stability limit, so that why explicit dynamic analysis is suitable for the wave propagation studies

3.4.4 Output requests

The Abaqus analysis products compute the values of many variables at every increment of a step. Usually we are interested in only a small subset of all of this computed data.. An output request consists of the following information:

- The variables or variable components of interest.
- The region of the model and the integration points from which the values are written to the output database.
- The rate at which the variable or component values are written to the output database.

When you create the first step, Abaqus/CAE selects a default set of output variables corresponding to the step's analysis procedure. By default, output is requested from every node or integration point in the model and from default section points. In addition, Abaqus/CAE selects the default rate at which the variables are written to the output database. You can edit these default output requests or create and edit new ones.

Default output requests and output requests that you modified are propagated to subsequent steps in the analysis. If you have a large model that includes the default output requests and requests output from a large number of frames, the resulting output database will be very large

When we create an output request, we can choose either field output or history output.

3.4.4.1Field output

Abaqus generates field output from data that are spatially distributed over the entire model or over a portion of it. In most cases you use the Visualization module to view field output data using deformed shape, contour, or symbol plots. The amount of field output generated by Abaqus during an analysis is often large. As a result, you typically request that Abaqus write field data to the output database at a low rate; for example, after every step or at the end of the analysis.

When you create a field output request, you can specify the output frequency in equally spaced time intervals or every time a particular length of time elapses. For an Abaqus/Standard analysis procedure, you can alternatively specify the output frequency in increments, request output after the last increment of each step, or request output according to a set of time points. For an Abaqus/Explicit analysis procedure, you can alternatively request field output for every time increment or according to a set of time points. For an Abaqus/CFD analysis procedure, you can alternatively specify the output frequency in increments.

When you create a field output request, Abaqus writes every component of the selected variables to the output database. We could then use the Visualization module to view a contour plot of displacements and velocities in the final loaded state.

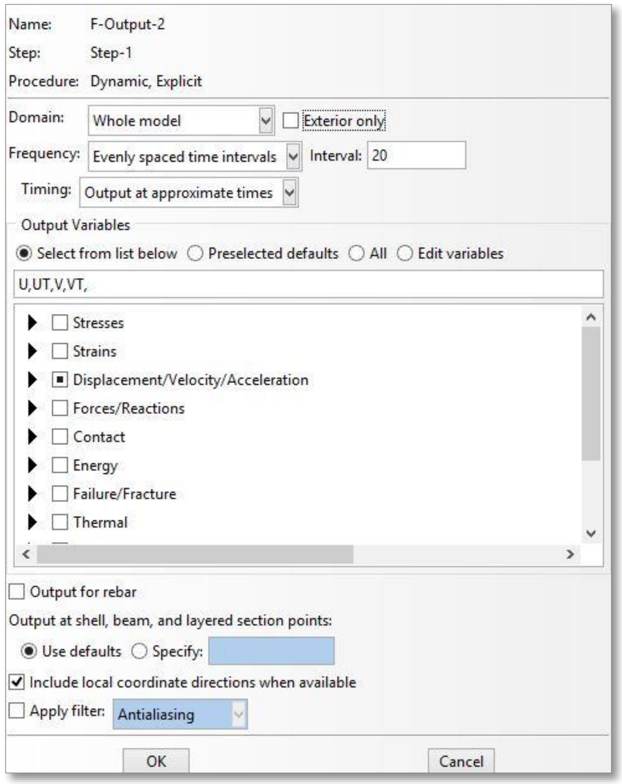


Fig3.3 Field output

3.4.4.2 History output

Abaqus generates history output from data at specific points in a model. In most cases you use the Visualization module to display history output using *X*–*Y* plots. The rate of output depends on how you want to use the data that are generated by the analysis, and the rate can be very high. For example, data generated for diagnostic purposes may be written to the output database after every increment. You can also use history output for data that relate to the model or a portion of the model as a whole; for example, whole model energies.

When you create a history output request, you can specify the output frequency in equally spaced time intervals or every time a particular length of time elapses. For an Abaqus/Standard analysis procedure, you can alternatively specify the output frequency in increments, request output after the last increment of each step, or request output according to a set of time points. For an Abaqus/Explicit analysis procedure, you can alternatively request history output in time increments. For an Abaqus/CFD analysis procedure, you can alternatively specify the output frequency in increments.

When you create a history output request, you can specify the individual components of the variables that Abaqus/CAE will write to the output database. For example, if you model the response of a cantilever beam with a load applied to the tip, you might request the following output after each increment of the loading step:

- The principal stress at a single node at the root of the beam.
- The vertical displacement at a single node at the tip of the beam.

You could then use the Visualization module to view an *X–Y* plot of stress at the root versus displacement at the tip with increasing load.

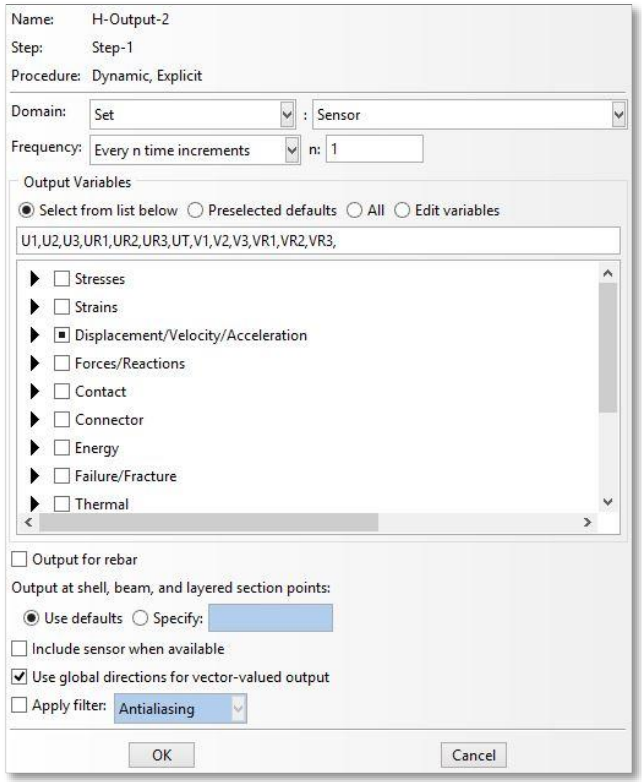


Fig3.4 History output

3.5 The Load module

Load module is used in order to define the appropriate loading conditions and assign the boundary conditions.In the load module we assigned excitation Load .We used load module to define and implement the following conditions.[13]

- Loads
- Boundary conditions
- Amplitude

Prescribed conditions in Abaqus/CAE are step-dependent objects, which mean that we must specify the analysis steps in which they are active. The load, boundary condition, and predefined field managers is used to view and manipulate the stepwise history of prescribed conditions. We can also use the Step list located in the context bar to specify the steps in which new loads, boundary conditions, and predefined fields become active by default.

For the amplitude of loads described above Amplitude toolset in the Load module is used to specify complicated time or frequency dependencies that can be applied to prescribed conditions

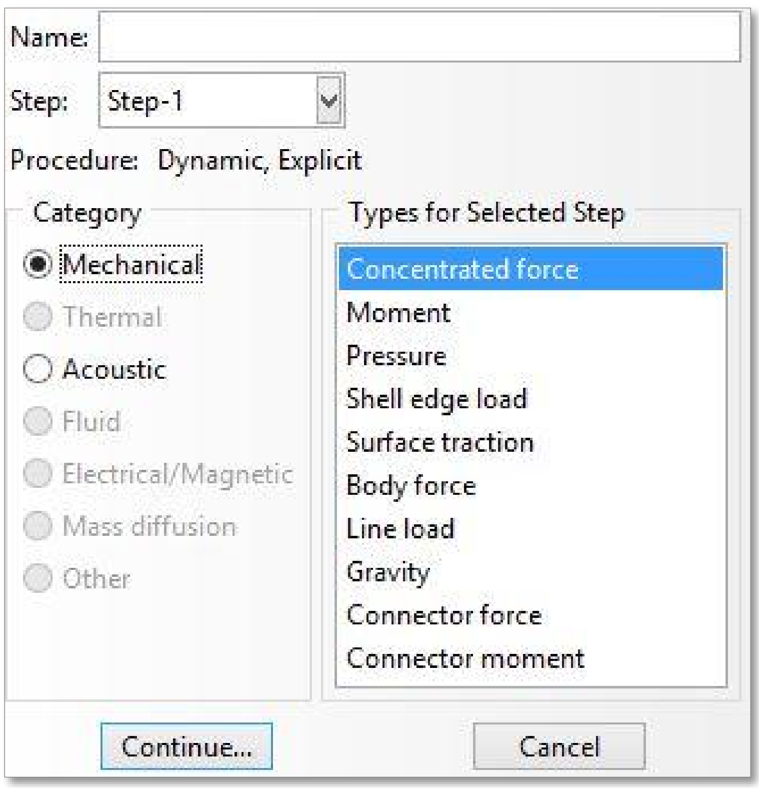


Fig: 3.5 Types of loads

3.5.1 Generation of Excitation Signal:

As discussed earlier in chapter 2 that the Rayleigh wave are dispersive in nature, so the excitation frequencies should be selected carefully in order to avoid the dispersion effect for this reasons the Rayleigh waves are generated at higher modes so that the group velocity V_g and Phase velocity V_P moves with the same velocity avoiding the dispersion phenomena, at these frequencies the Rayleigh wave behave as ordinary wave and making it easy to generate and helps in signal processing.

Rayleigh wave signal is generated by a localized impact method as in Abaqus Explicit Analysis we can generate the Rayleigh waves by taking into account for the effective forces.

We used the Amplitude toolset in the Load module to specify time or frequency dependencies that can be applied to prescribed conditions. The Set tools in the Load module allow us to define and name regions of your model to which you would like to apply prescribed conditions.

A periodic excitation source is chosen with different resonance frequencies of sphere as discussed in chapter 2.

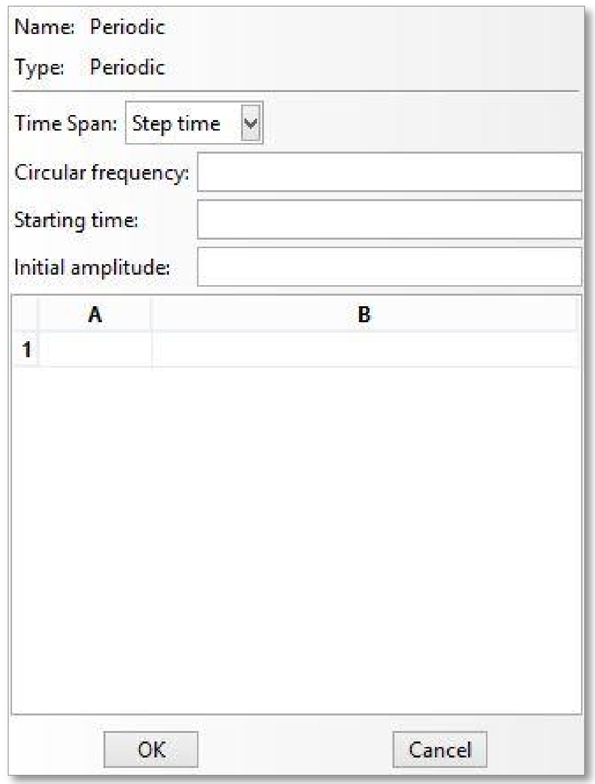


Fig:3.6 Defining Periodic Amplitude

After selecting the Dynamic, Explicit and the time step is the 10ms as according to Table 4-2, this value meets its criterion and this simulation can obtain more accurate results. For the boundary condition aspect, applying effective displacements on related nodes in contact with piezoelectric actuator is suitable in Abaqus /Explicit, The node at which excitation is applied is constraint so not to rotate in any direction.

3.

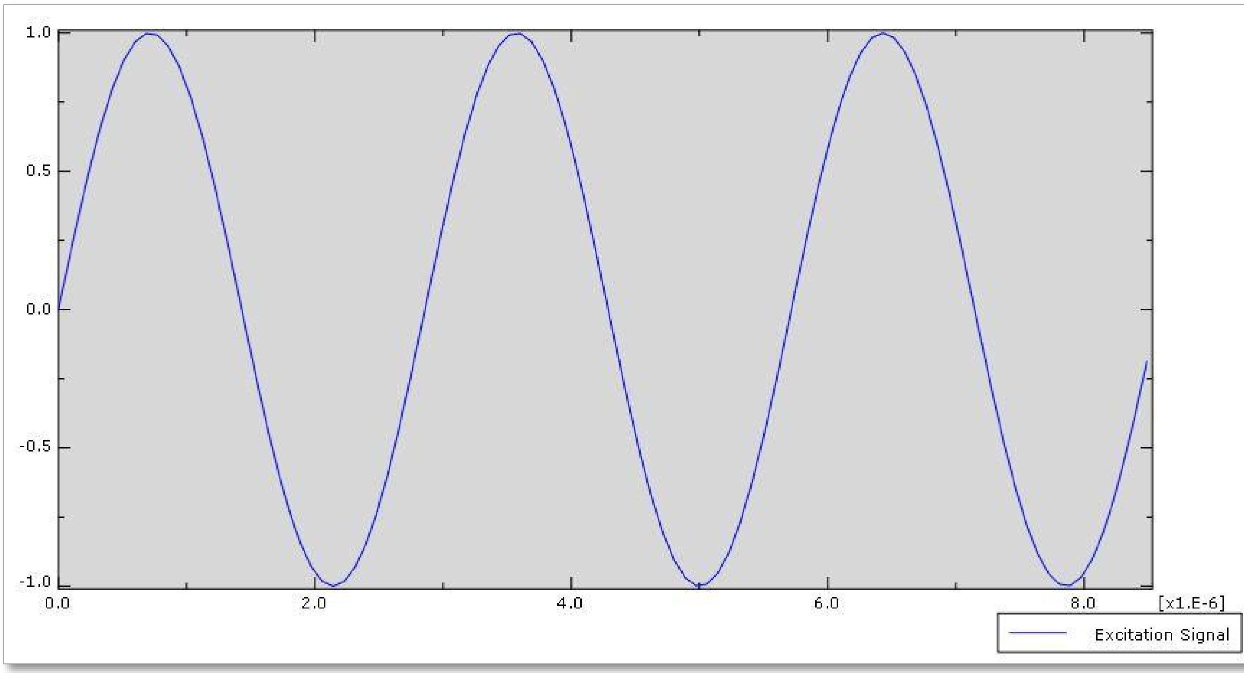


Fig: 3.7 Excitation signal

Creating loads

During load creation, we specified the name of the load, the step in which load is activated is the concentrated force and direction of load as shown in the Fig 3.8 , and the region of the assembly to which load is applied must be mentioned.

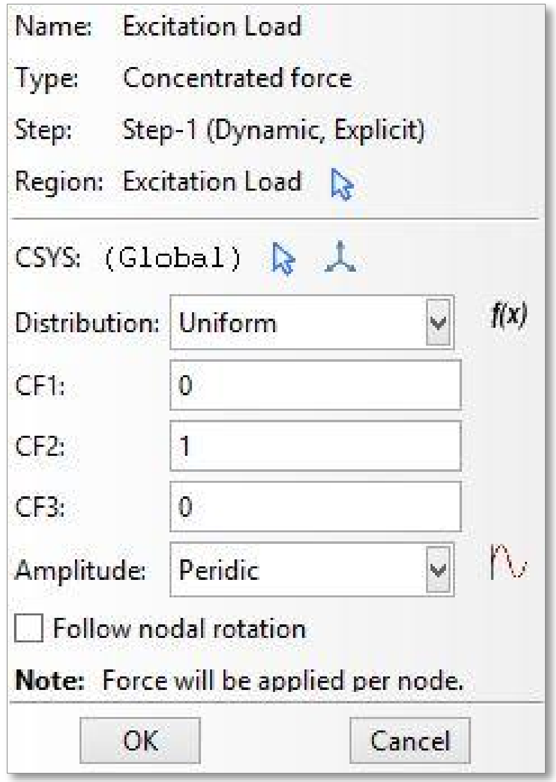


Fig: 3.8 Amplitude of load

3.5.2 Boundary conditions

During creation of boundary condition, we specified the name of the boundary condition, the step in which to activate the boundary condition is the displacement/rotation boundary condition, , and the region of the assembly to which this boundary condition is applied must be mentioned during assigning boundary conditions.

3.5.3 Displacement/rotation boundary condition

Displacement/rotation boundary condition is used to constrain the movement of the selected degrees of freedom to zero or we can prescribe the value for the displacement or rotation for each selected degree of freedom

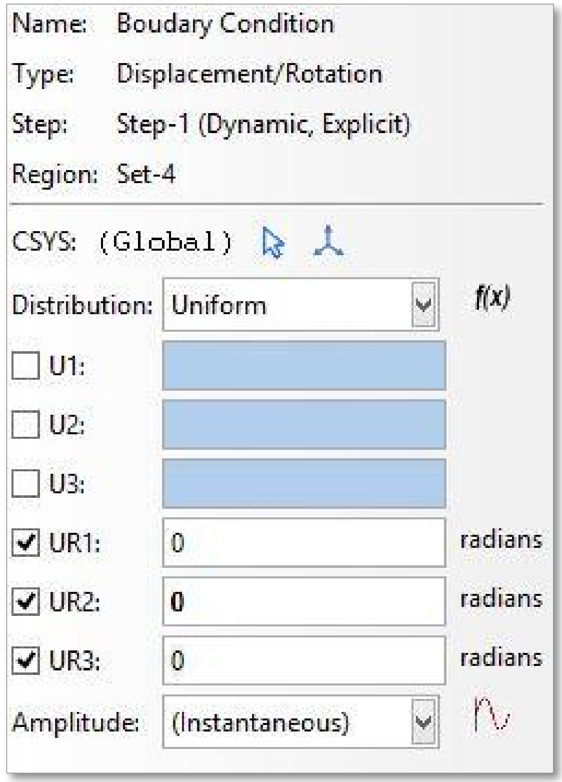


Fig3.9: Displacement/rotation boundary condition

3.6 Mesh module:

The Mesh module implements that sanction us to engender meshes on components and assemblies engendered within Abaqus/CAE. In addition, the Mesh module contains functions that verify a subsisting mesh. This chapter covers the following topics:

The Mesh module sanctions are utilized to engender meshes on components and assemblies engendered within Abaqus/CAE. Different levels of automation and control are available so that we can engender a mesh that meets the satisfies the of our analysis. As with engendering components and assemblies, the process of assigning mesh attributes to the model—such as seeds, mesh techniques, and element types—is feature predicated. As a result we can modify the parameters that define a component or an assembly, and the mesh attributes that you designated within the Mesh module are regenerated automatically.

The Mesh module provides the following features:

- Tools for prescribing mesh density at local and global levels.
- Model coloring that indicates the meshing technique assigned to each region in the model.
- A variety of mesh controls, such as:
    - Element shape
    - Meshing technique
    - Meshing algorithm
- A tool for assigning Abaqus/Standard, Abaqus/Explicit, or Abaqus/CFD element types to mesh elements. The elements can belong either to a model that was created or to an orphan mesh.
- A tool for verifying mesh quality.
- Tools for refining the mesh and for improving the mesh quality.

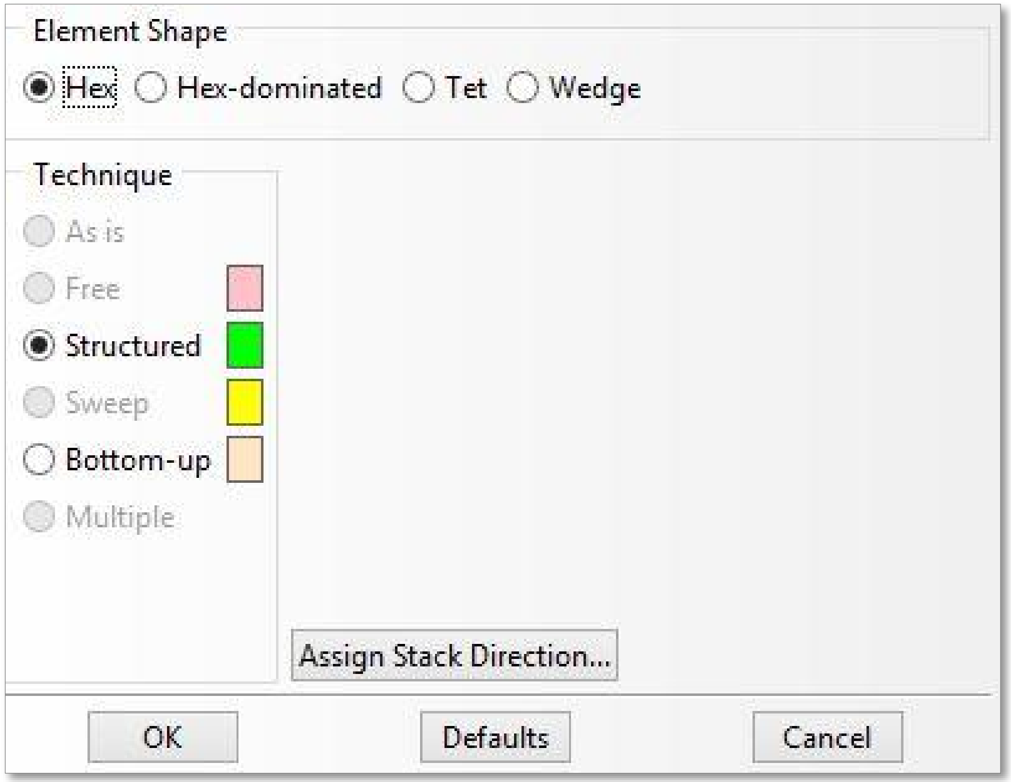


Fig: 3.10Mesh Elements shape

3.6.1 The meshing

To engender an acceptable mesh, we adopted the following process

3.6.2 Assigning mesh attributes and setting mesh controls

The Mesh module provides a variety of implements that sanction us to designate different mesh characteristics, such as mesh density, element shape, and element type.

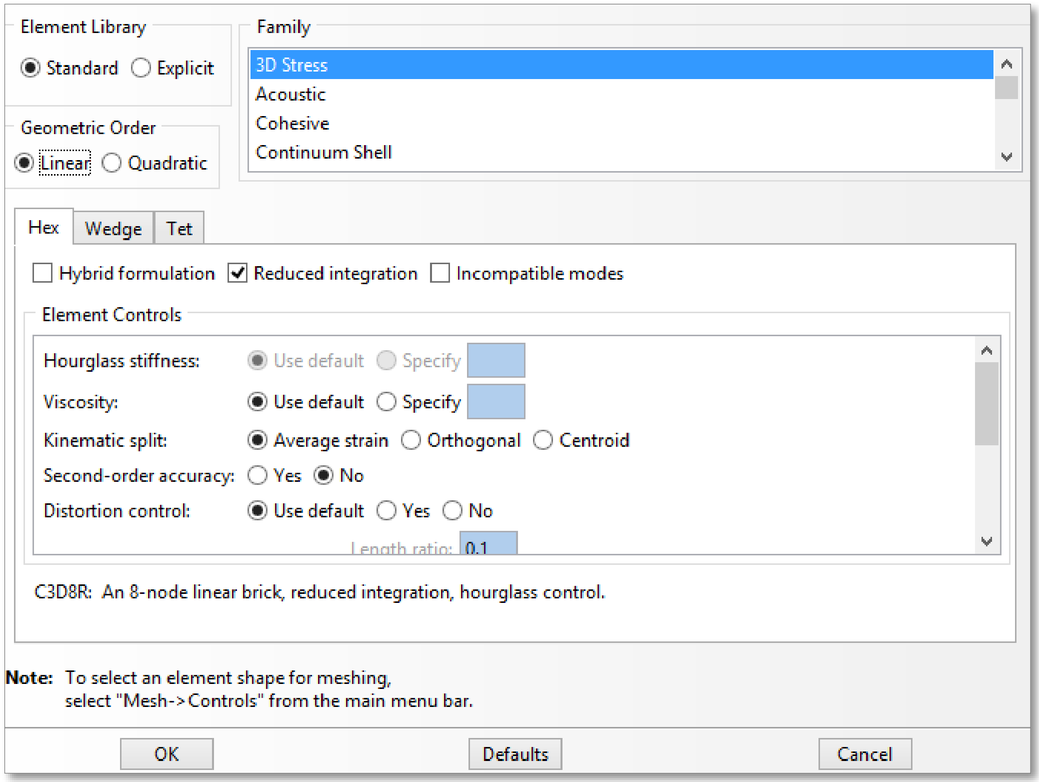


Fig: 3.12 Mesh Element Types

3.6.3 Generation of the mesh

The Mesh module utilizes a variety of techniques to engender meshes. There are different mesh techniques provide us with different calibers of control over the mesh.

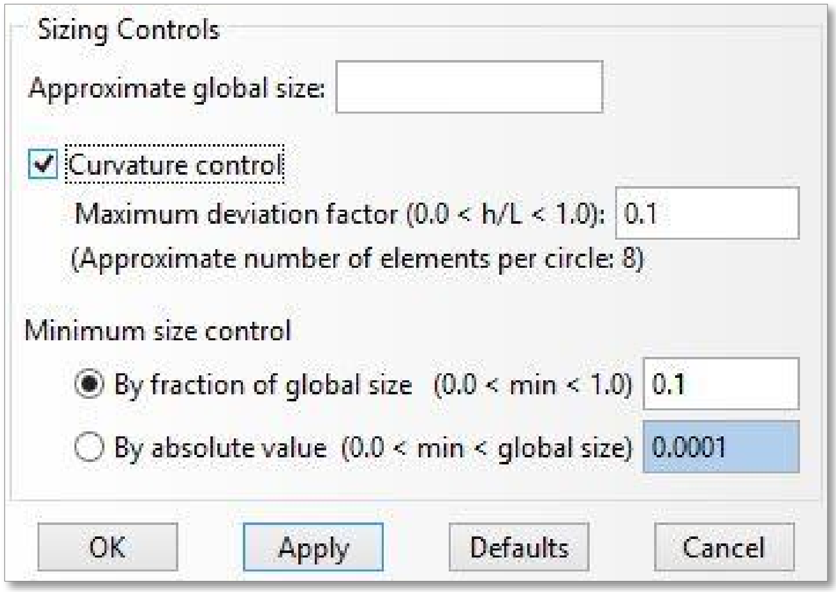


Fig: 2.13 Seeding the part

3.6.4 Optimization of the mesh

we can assign remeshing rules to regions of our model. Remeshing rules enable successive refinement of your mesh where each refinement is predicated on the results of an analysis.

3.6.5 Verification of the mesh

The verification implements provide us with information concerning the quality of the elements utilized in a mesh.

3.7 The Job module

After finishing all of the tasks involved in defining a model (such as defining the geometry of the model, assigning section properties, and defining contact), we utilized the Job module to analyze our model. The Job module sanctions to engender a job, to submit it for analysis, to find out the errors or to monitor the progress of model.

CHAPTER 4

Results and Discussion

4.1 Introduction:

Chapter 4 presents the results obtained from simulations of non destructive testing of bearing balls having diameter 33.3 mm using surface Rayleigh waves.The excitation signal is generated and one pole of the sphere and on the opposite pole the response of the ultrasonic waves is measured. On the basis of this response the presence of defects can be detected and also characterization of the defects is analyzed on the basis of data extracted from the measured response.

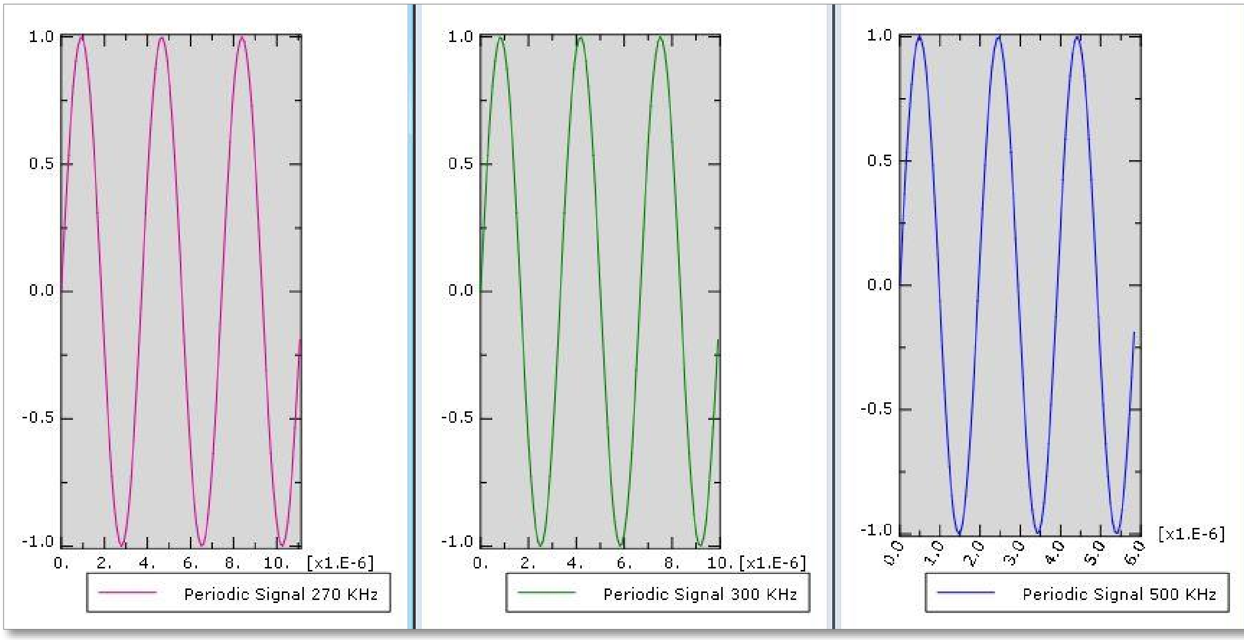
Excitation frequencies chosen for simulations are the resonance frequencies of sphere which are calculated from the normalized curve [2.1].

A circular defect having diameter 20 micron is inserted using revolve cut command at a depth of 200 micron from the surface of sphere and the responses are measured at different resonance frequencies.

The radial component of displacement is measured at the sensor points shown in Fig 4.2 and the comparison of displacement measured in radial direction at sensor is made between the non defected sphere and defected sphere.

4.2 Input excitation signal frequencies:

Sphere is excited at different resonance frequencies for ball having diameter 33.3mm derived from the normalized curved for the angular frequency shown in Fig 3.1.Specifically sphere is excited at 270 KHz, 300 KHz and 500 KHz for a step time of 0.0001 sec mentioned in table 3.2.



(a) (b) (c)

Fig 4.1 Input excitation signal frequencies (a) 270 KHz (b) 300 KHz (c) 500 KHz

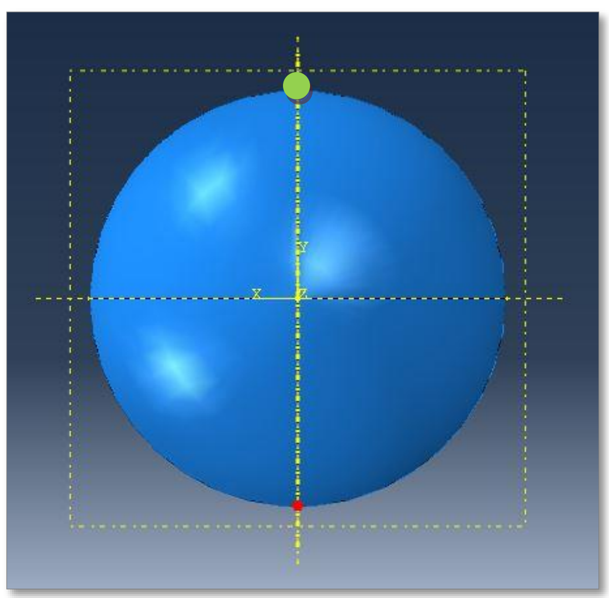


Fig:4.2 Position of excitation (Red) and sensor (Green)

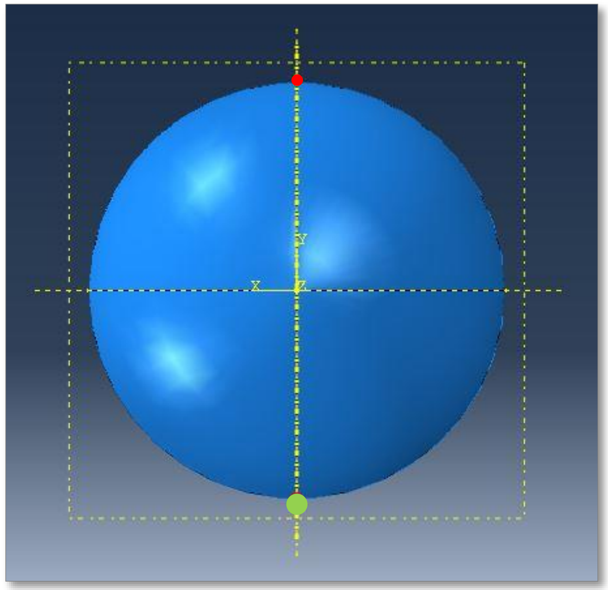


Fig:4.3 Position of excitation (Red) and sensor (Green) are reversed.

4.3 Defect position:

Defect of diameter 20 micron is inserted at a depth of 200 microns below the outer surface shown in Fig 4.2 below the meridian. The defect is simulated by creating the revolved cut by the rotating the cross section about construction line which serves an action of revolution.

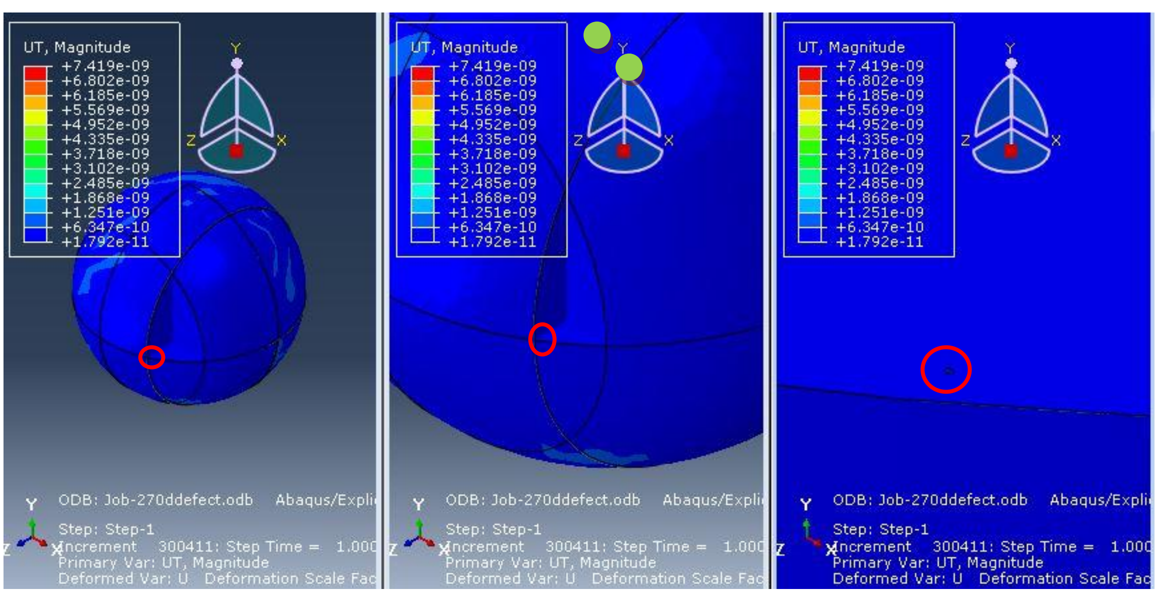
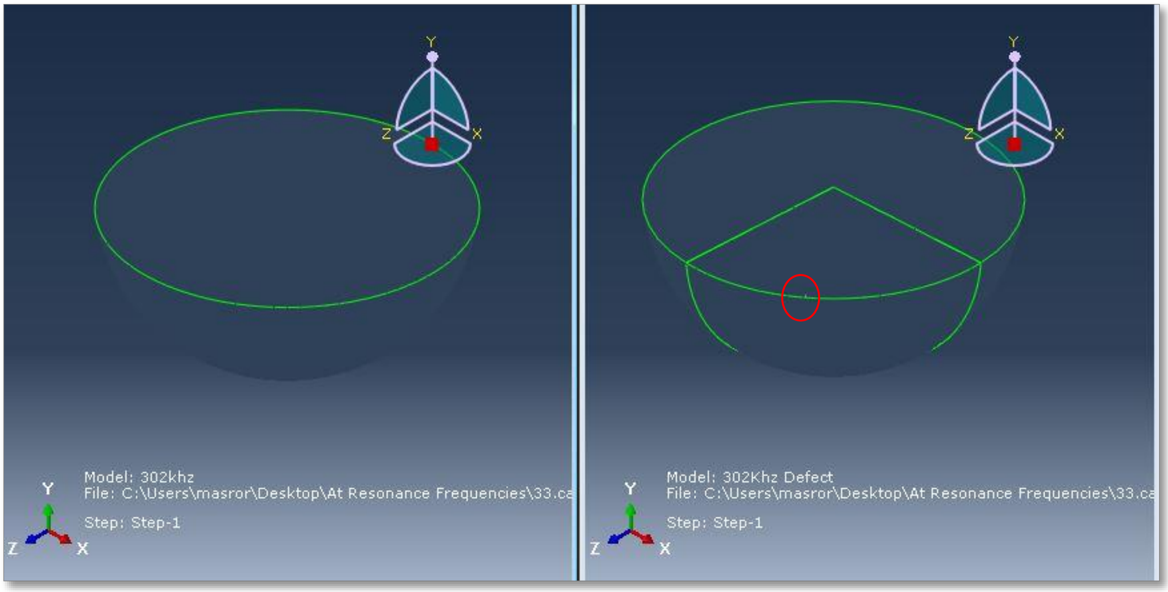


Fig: 4.4 Position of circular defect having diameter 20micorn at depth of 200micron



(a) (b)

Fig4.5 Sphere without defect, (b) Sphere with defect -20microns diameter located at a depth of 200microns

Excitation is provided at the bottom of the sphere and the response is measured at the opposite pole of the sphere shown in Fig 4.2. The responses at different natural frequencies of the steel sphere are discussed below and comparison is made between the defected balls and with non defected balls.

4.4 Investigation of Response signal:

The bearing ball is analyzed in Abaqus 6.14 using the Explicit dynamic procedure discussed in section 3.4.3. The analysis focuses on the attenuation in the measured normal displacement signal at the sensor position and the change is the displacement signal between the defected and non defected sphere is investigated. The response at the different resonance frequencies is discussed under this section.

4.4.1 Response at 270 kHz:

For this analysis, the 270 kHz excitation signal that is shown in Section is used to generate a response. At this low frequency ,At lower frequencies Rayleigh waves are not sensitive to the surface defects making difficult to locate defect present near the surface i.e. defect of 20 microns at a depth of 200 micron from the surface is not so easy to recognized as shown in the Fig.4.1

These waves are not the bulk waves so the method TOA is not suited as it works better for the detection of defects were bulk waves are used to investigate thick structures.

However the best methods is to measure the displacement response and by analyzing the displacement of the normal component we can detect the presence of the defect and somehow the position of the defect but currently we are not so much interested in doing the quantitative analysis for the position of sphere .

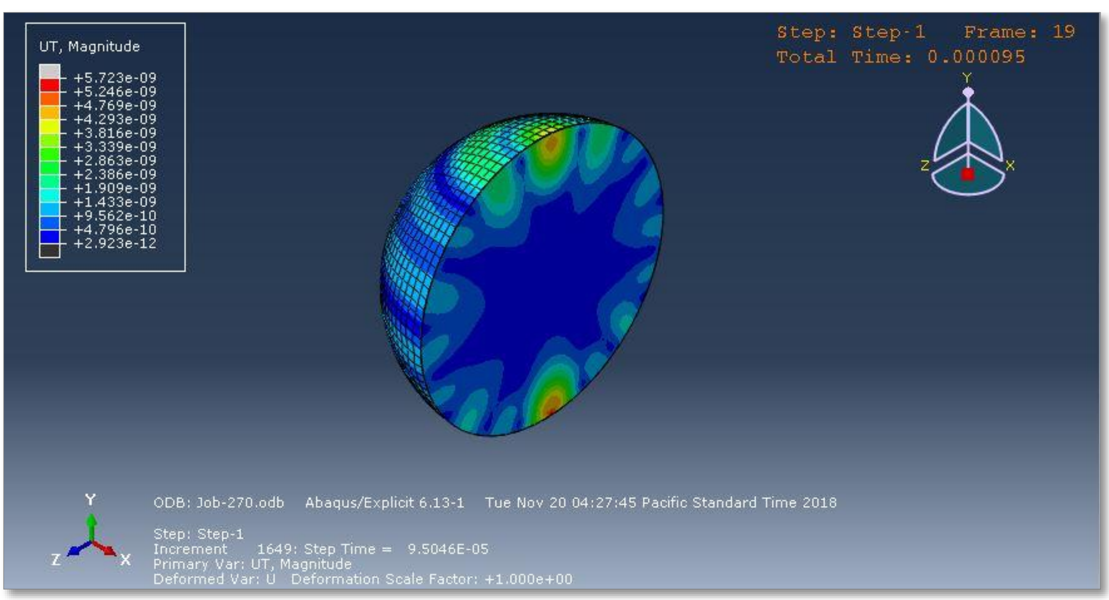


Fig 4.6: Propagation of Rayleigh waves at frequency 270 KHz

Rayleigh waves are excited at one of the pole of sphere and the radial component of displacement is measured .The benchmark displacement signal measured at the sensor position is shown in Fig. 4.3

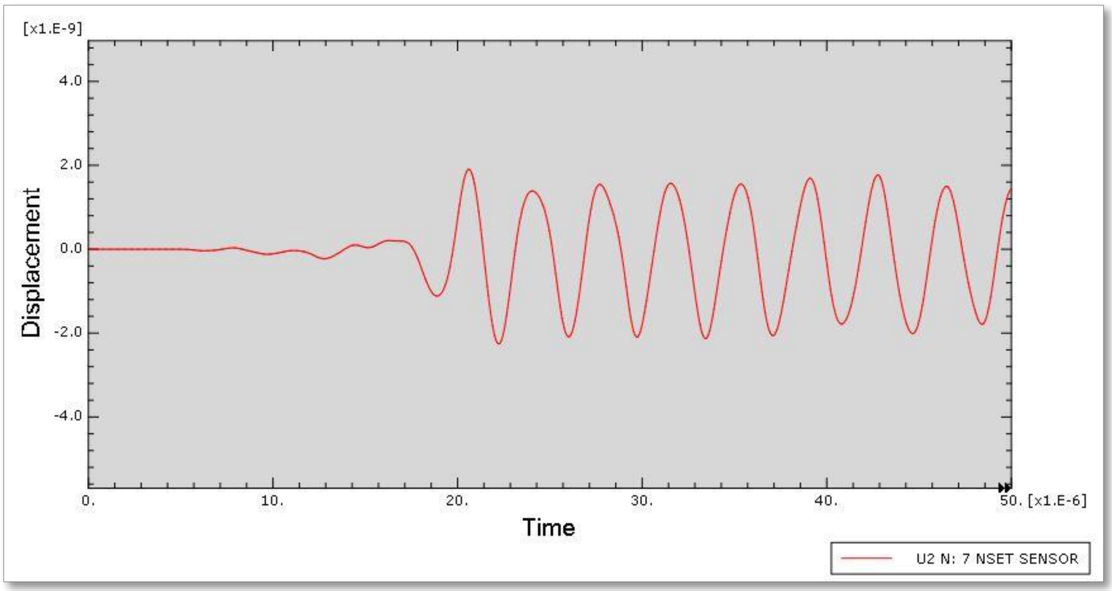


Figure 4.7 Displacement signals from FE dynamic simulations of steel sphere without a defect in the radiall direction at 270 KHz

At this frequency since the defect is small there is little attenuation since Rayleigh waves at low frequencies are not so much sensitive to the defects present near the surface.

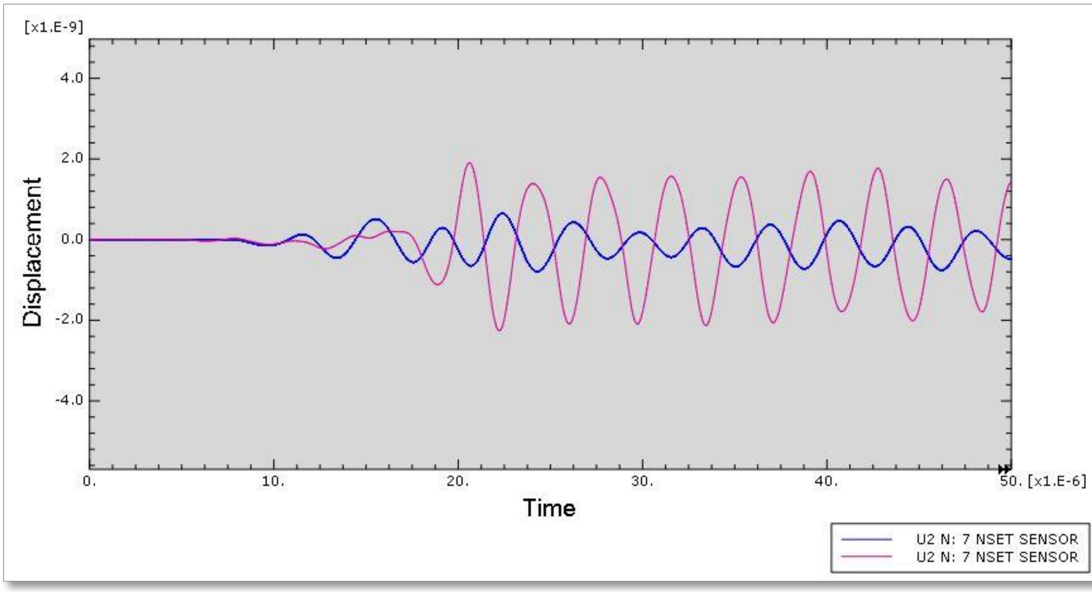


Fig: 4.8 Comparison of Displacement Signals from FE dynamic simulations of steel sphere with (Blue) and without defect (Red)

For the same frequency the position of the excitation source and sensor are changed in order to evaluate the position of defect on the measured signal. The amplitude of the measured signal seems to be same as in the previous case however there is phase change in the measured signal when we changed the position of sensors and excitation source. The responses are shown in Fig 4.9

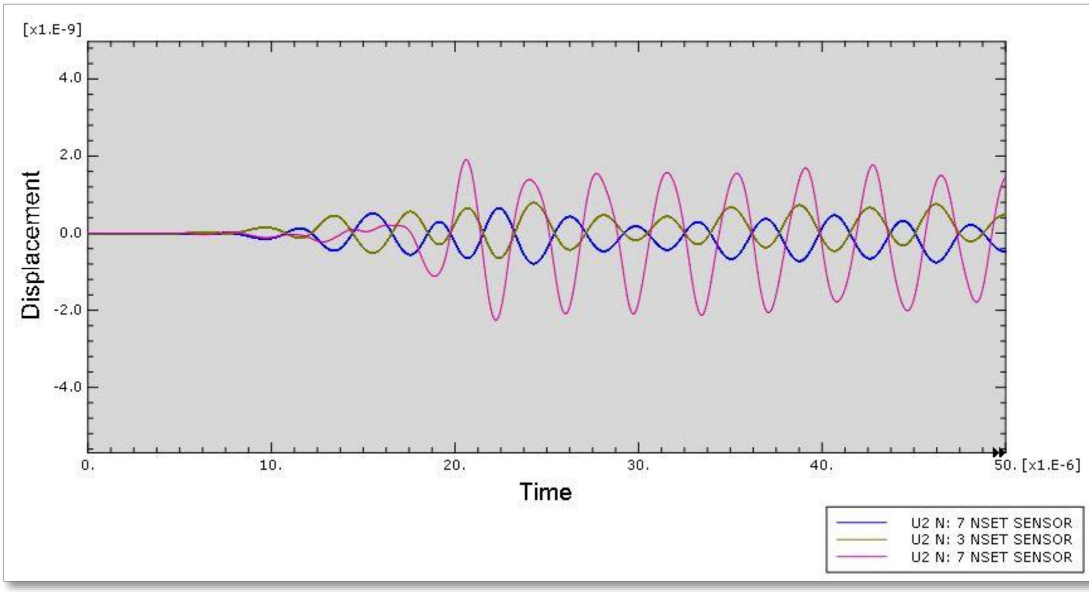


Fig: 4.9 Displacement Signals from FE dynamic simulations of steel sphere with and without defect (Red).Blue and gray corresponds to Fig 4.2 and 4.3 respectively.

4.4.2 Response at 300 kHz:

As discussed in literature review (chapter 2) that the penetration depth of the Rayleigh waves are dependent on the frequency as the value of n increase the small defects located near the surface are most sensitive to Rayleigh waves which can seen under this frequency when compared with 270 KHz

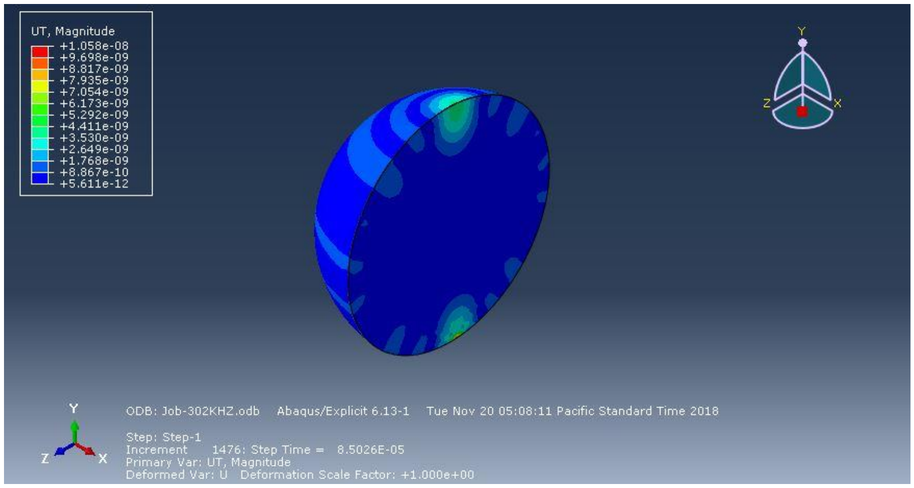


Fig: 4.10 Propagation of Rayleigh waves with frequency 300 KHz

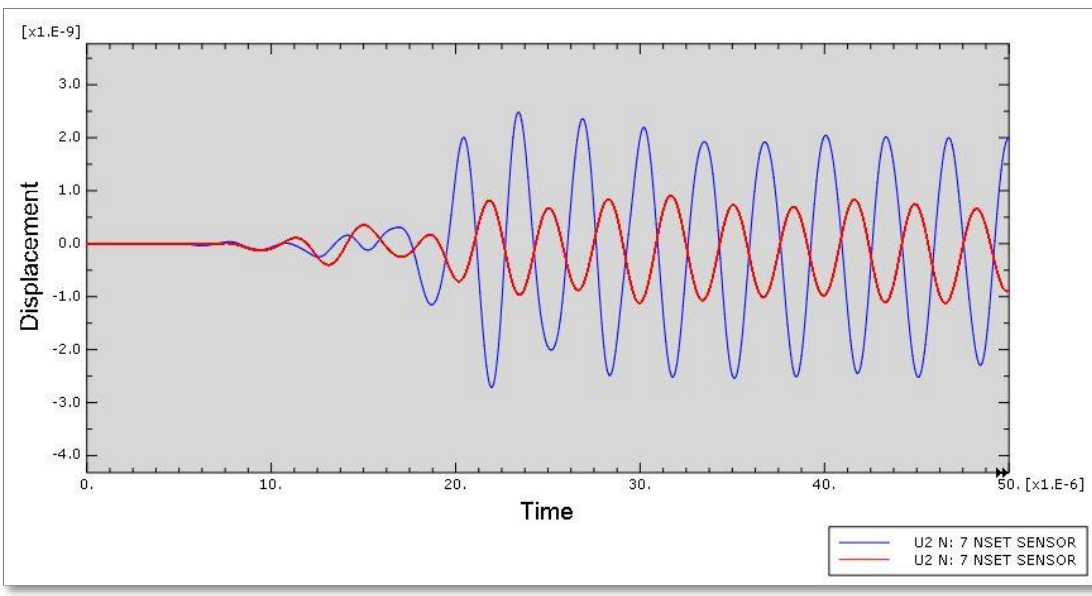


Fig: 4.12 Displacement Signals from FE dynamic simulations of steel sphere with (Red) and without defect (Blue) at 300 KHz

Position of the excitation source and the sensors are changed by 180 degree and the responses as shown in Fig 4.13.The response is measured in order to find out the effect of the defect on the response signal. It was noticed that if the defect is located far away from the excitation source the attenuation in the signal is more significant as compared if the defect lies near to excitation source .The comparison of the response signal is shown in Fig 4.8

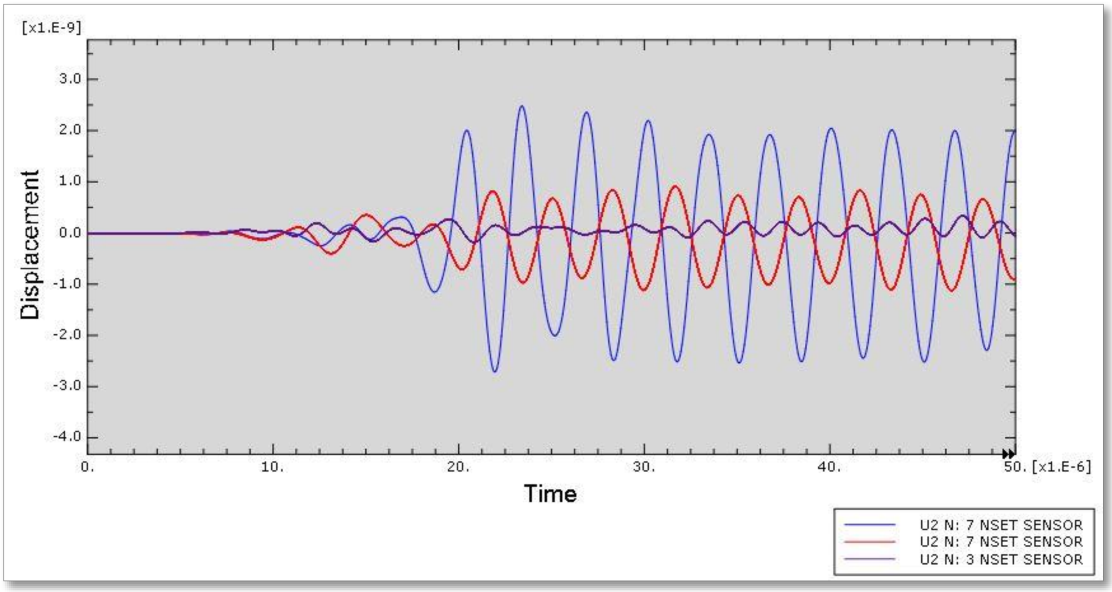
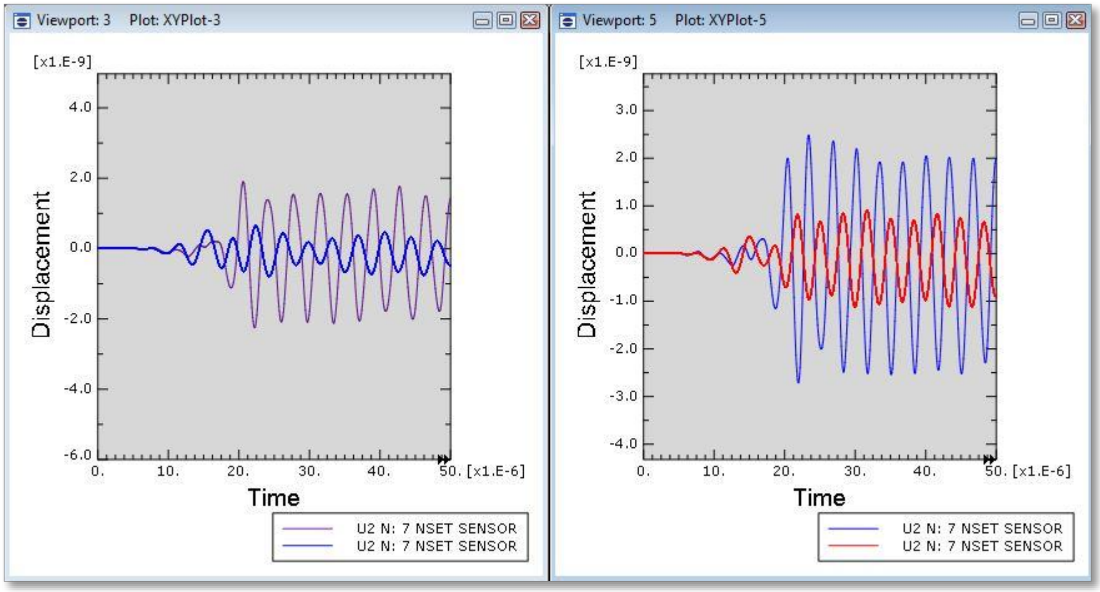


Fig: 4.13 Displacement Signals from FE dynamic simulations of steel sphere with and without defect



(a) (b)

Fig: 4.14 Comparison of Displacement Signals from FE dynamic simulations (a) 270 and (b) 300

(a) Benchmark (Gray), Defected (blue) (b) Benchmark (blue), Defected (Red)

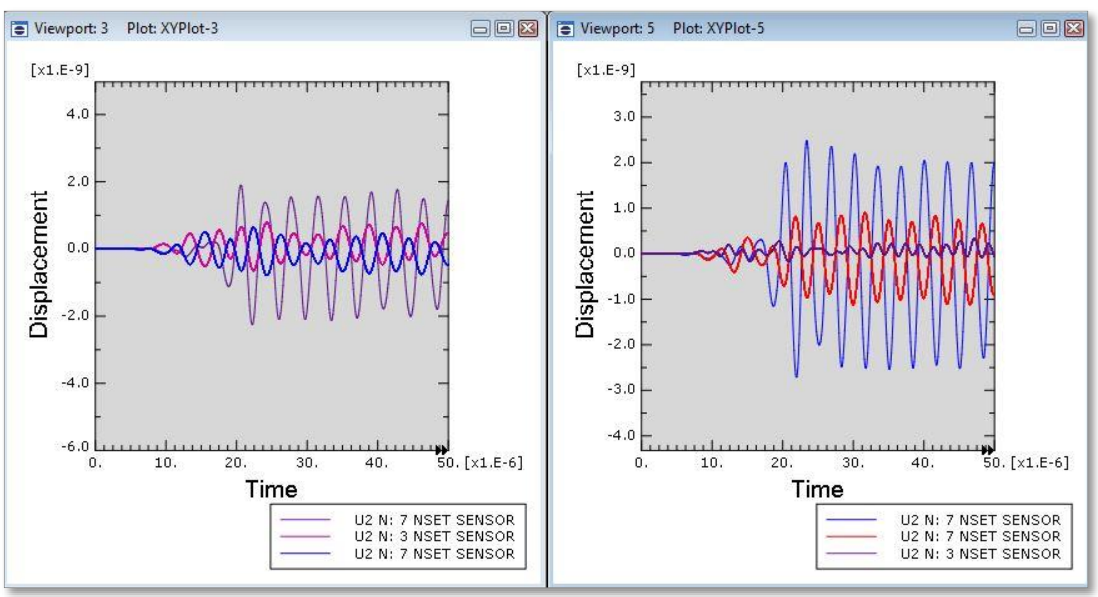


Fig: 4.15 Comparison of Displacement Signals from FE dynamic simulations (a) 270 and (b) 300 with reversing the position of source and sensor

4.4.3 Response at 500 kHz:

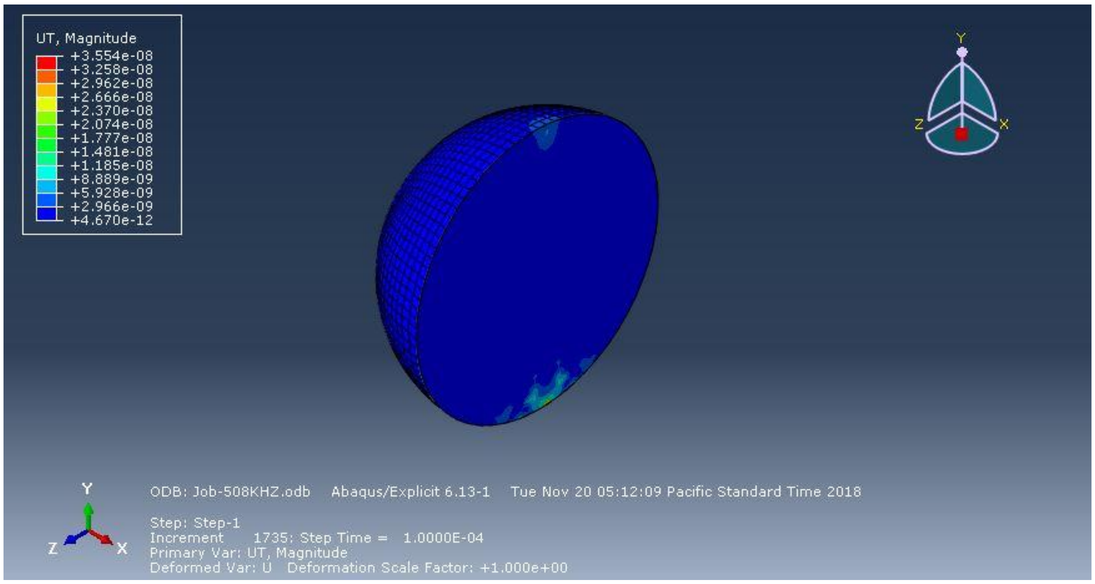


Fig: 4.16Propagation of Rayleigh waves with frequency 500 KHz

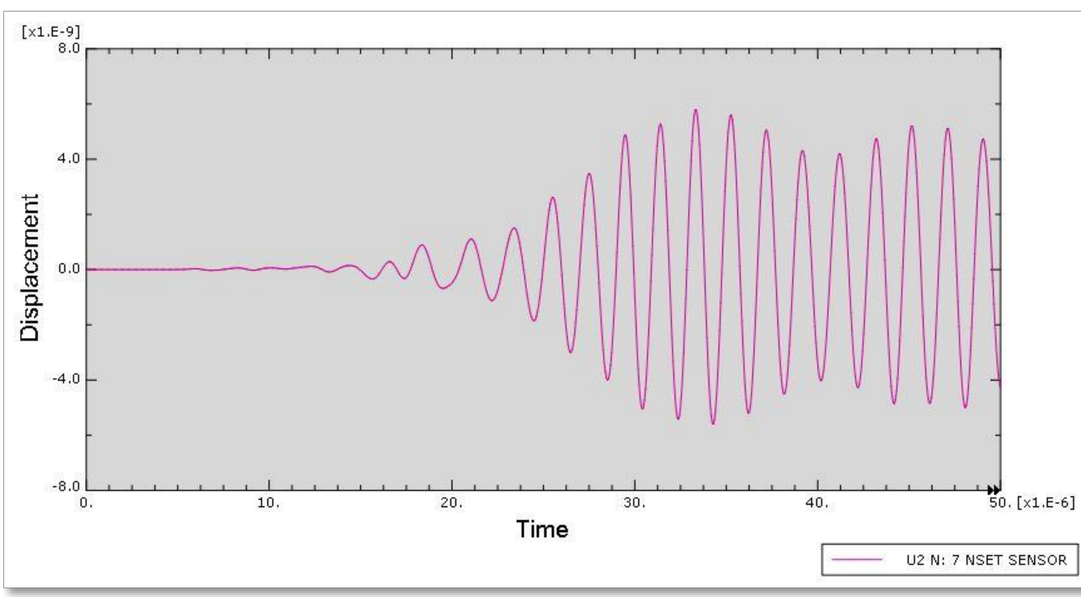


Figure 4.17 Displacement signals from FE dynamic simulations of steel sphere without a defect in the normal direction at 500 KHz

At this higher value of frequency the Rayleigh waves are very sensitive for the defects present near the surface which can be seen in Fig.4.13

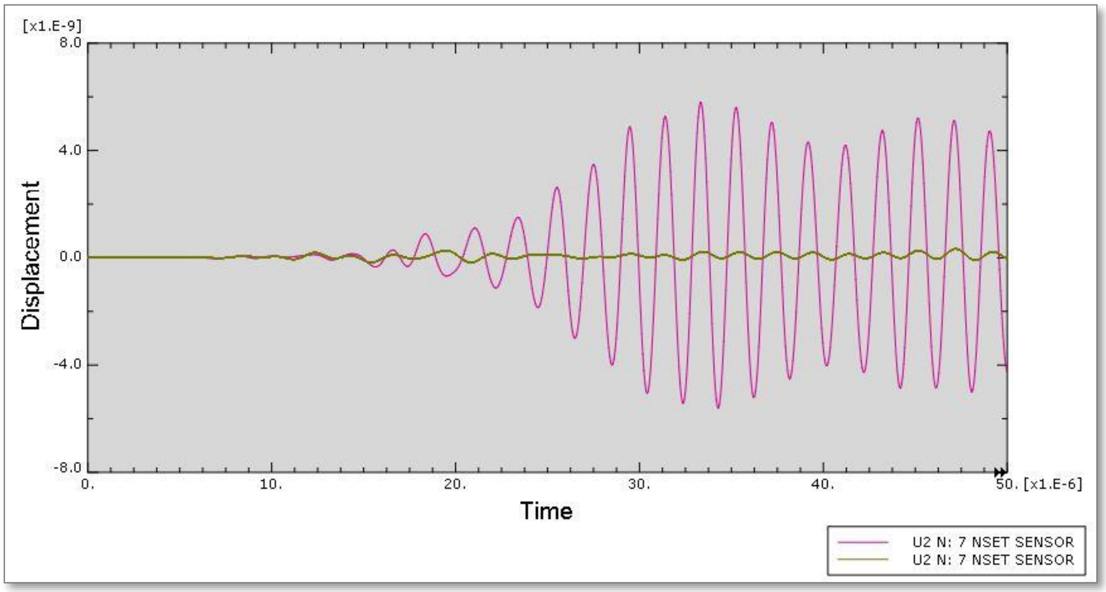


Fig4.18: Displacement Signals comparison from FE dynamic simulations of steel sphere with (gray) and without defect (pink) at 500 KHz

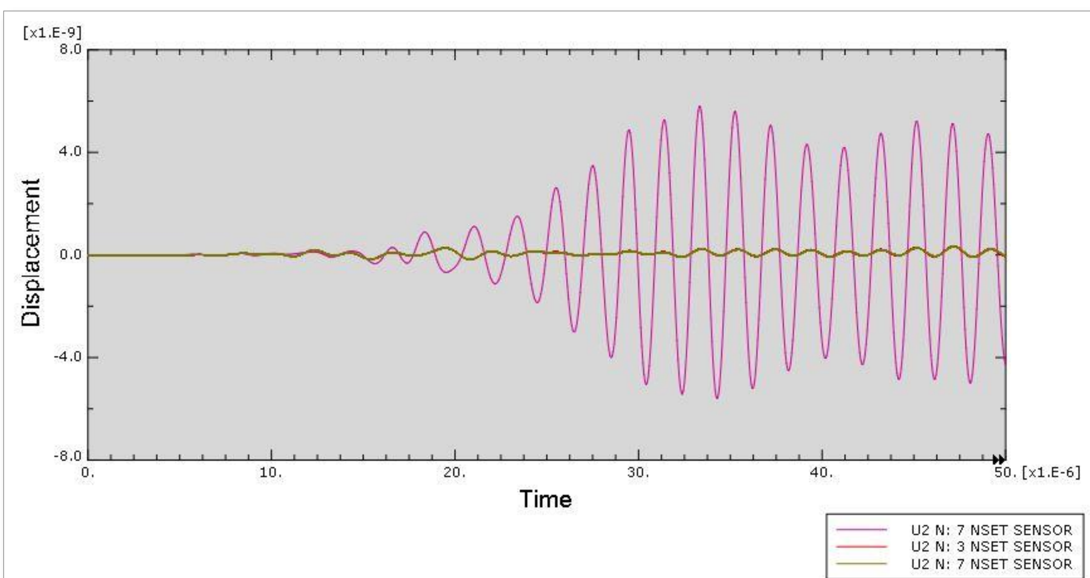
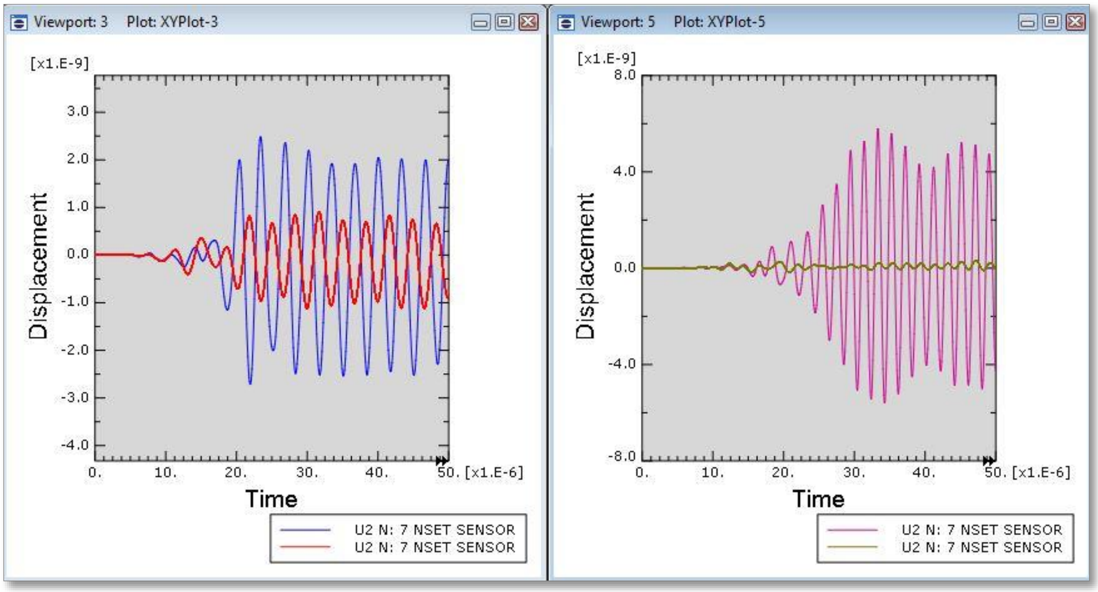


Fig: 4.19 Displacement Signals comparison from FE dynamic simulations of steel sphere with (gray) and without defect (pink) at 500 KHz with reversing the position of source and sensor.

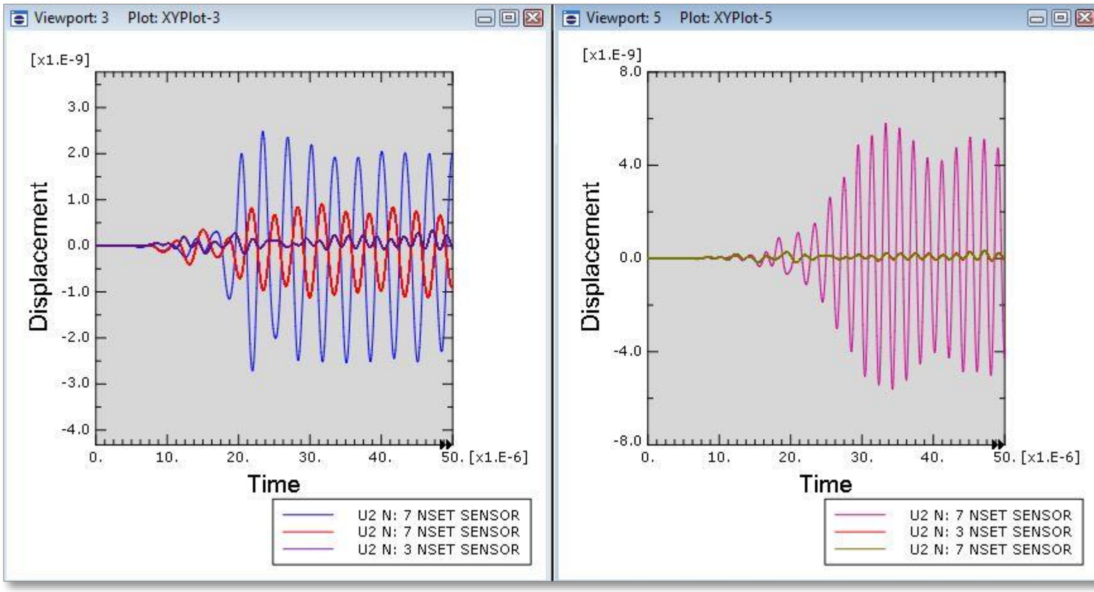


(a) (b)

Fig: 4.20 Comparison of Displacement Signals from FE dynamic simulations (a) 300 and (b) 500

The results in Fig 4.20 above are in accordance to the experimental predictions [10] as we increase the frequency of the excitation signal the same defects shows a significant attenuation in the response signal.

Comparison has been done in Fig 4.21 between frequencies 300 kHz and 500 kHz also by changing the position of the excitation source and sensor.



(a) (b)

Fig: 4.21 Comparison of Displacement Signals from FE dynamic simulations (a) 300 and (b) 500

With reversing the position of source and sensor

Numerical data has been extracted from the above graphs for the displacement attenuation for different frequencies shown in Table 5.1 along with reversing the position of excitation and sensor in Table 5.2

4.5 Extracted Data from measured response:

Resonance Frequencies [KHz]		Normal component of displacement for the balls without Defect[nm]	Normal component of displacement for the balls with Defect[nm]	Attenuation in the response signal[nm]
1	270	2.0	0.5	1.5
2	300	2.5	1.0	1.5
3	500	4.5	0.2	4.3

Table 5.1: Attenuation in displacement at different frequencies

Graphical representation of measured responses are plotted and shown in Fig 4.19,it can seen at higher frequency there is significant attenuation in the measured signal at the sensor (top) making sub-surface defects more sensitive.

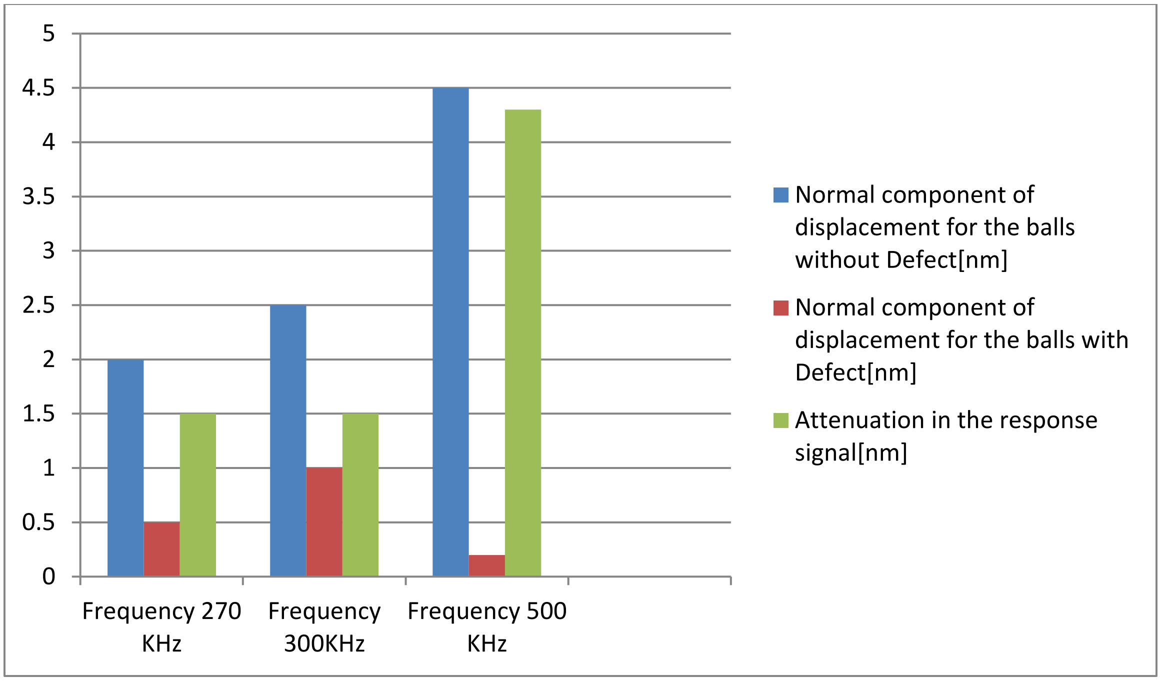


Fig: 4.22 Graphical representation and comparison of measured responses (sensor positioned at top)

Resonance Frequencies [KHz]		Normal component of displacement for the balls without Defect[nm]	Normal component of displacement for the balls with Defect[nm]	Change of Attenuation in the response signal[nm]
1	270	2.0	0.5	1.5
2	300	2.5	0.5	2.0
3	500	4.5	0.1	4.4

Table 5.2: Attenuation in displacement at different frequencies by reversing the position of sensor

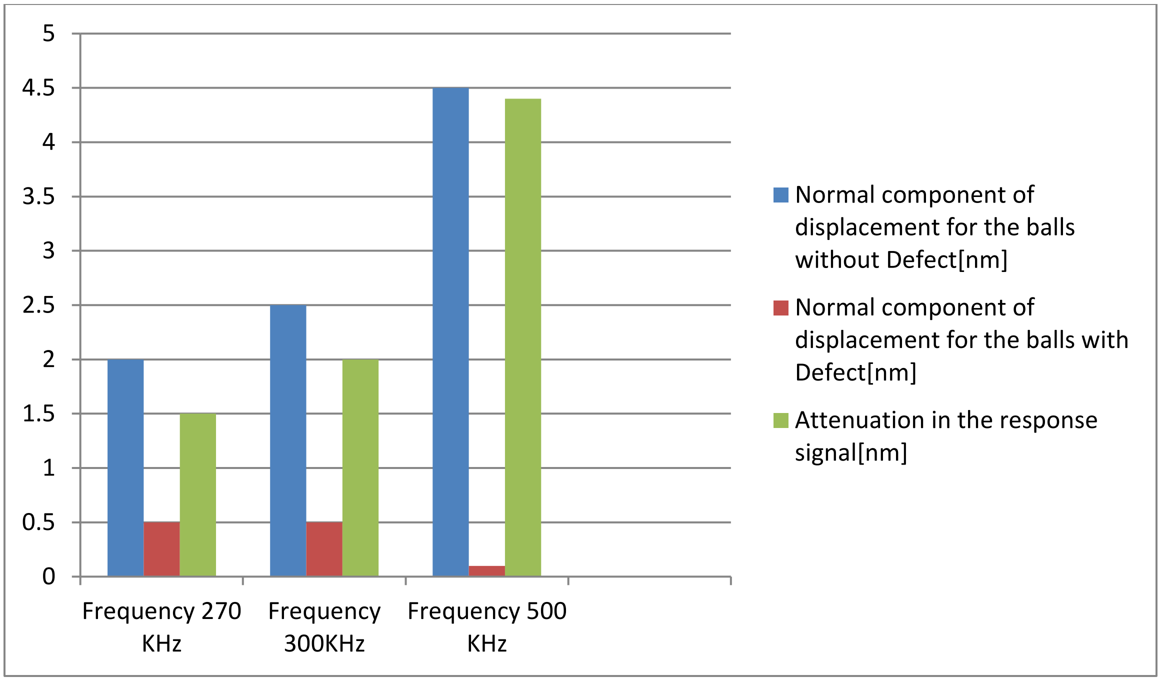


Fig: 4.23 Graphical representation and comparison of measured responses (sensor positioned at Bottom)

At lower frequencies change in the response signals are not significant as accordance to the theory discussed in chapter 2.However moving towards higher frequencies, we started seeing a significant attenuation in measured response.

4.6 Conclusion:

Rayleigh waves have been excited at resonance frequencies of steel sphere having diameter 33.3mm by using Explicit Dynamic Analysis in Abaqus 6.14. The excitation signal is provided at one of the pole of sphere and at the opposite poles response signal was measured .The normal component of vibration was measured and compared with the defected sphere having a circular depth of 20 microns located at a depth of 200 microns. By measuring the attenuation of the response signal we analyzed the presence of defects which is significant at the resonance frequencies. With the increase of resonance frequencies the defects present near the surface become more sensitive as shown in chapter 4.

4.7 Recommendations:

In this thesis work we were interested in detecting the presence of the defects under the surface which is of major importance in ball bearings since the maximum stress lies below the surface at certain depth depending upon the elliptical contact of ball bearings under working conditions while working at high frequencies. At such frequencies the dispersion effect of Rayleigh waves has no effect on the propagation of the waves. In order to evaluate the portion of sphere near to center generation of dispersion curve is necessary.

During Experimental generation of Rayleigh waves is highly recommended to generate the Rayleigh waves by using laser ultrasonic in order to avoid the contact issues discussed in chapter to avoid mechanical contact.

Chapter 5

Experimental Setup

5.1 Introduction

Vibration analysis of various machines is a powerful diagnostic tool enabling to evaluate a dynamic behavior and the status of the object under a test. For this purpose it is necessary to measure instant amplitudes and phase of vibrations of the surface of the investigated object. The measurements may be performed by various sensors, such as piezoelectric accelerometers, electromagnetic sensors, fixed to the vibrating surface. Most of the sensors measure acceleration or a vibration velocity, but not an absolute displacement of the vibrating surface. The most attractive are sensors, which used non-contact techniques. We have developed an ultrasonic sensor enabling to perform absolute measurements of surface displacements (vibration) by means of high frequency ultrasonic waves.

5.2 Time and Frequency Analysis

Structural vibration can be measured by electronic sensors that convert vibration motion into electrical signals. By analyzing the electrical signals, we can know about the condition of structure by analyzing the nature of the vibrations, each domain provides a different view and insight into the nature of the vibration. Time domain analysis starts by analyzing the signal as a function of time. An oscilloscope, data acquisition device, or signal analyzer can be used to acquire the signal.

The plot of vibration versus time provides information that characterizes the behavior of the structure. Its behavior can be characterized by quantifying the maximum vibration (or peak) level, or finding the period, (time between zero crossings), or estimating the decay rate (the amount of time for the envelope to decay to near zero). These parameters are the typical results of time domain analysis.

Frequency analysis additionally provides valuable information about structural vibration. Any time history signal can be transformed into the frequency domain. The most mundane mathematical technique for transforming time signals into the frequency domain is called the Fourier Transform, Fourier Transform theory verbalizes that any periodic signal can be represented by a series of pristine sine tones. For example square wave can be constructed by integrating up a series of sine waves; each of the sine waves has a frequency that is a multiple of the frequency of the square wave. The amplitude and phase of each sine tone must be carefully chosen to get just the right waveform shape. When utilizing a inhibited number of sine waves.

In structural analysis, usually time waveforms are measured and their Fourier Transforms computed. The Fast Fourier Transform (FFT) is a computationally optimized version of the Fourier Transform. The third plot in Figure 4 also shows the measurement of the square wave with a signal analyzer that computes its Fast Fourier Transform. With test experience, you will gain the ability to understand structural vibration by studying frequency data.

In structural analysis, conventionally time waveforms are quantified and their Fourier Transforms computed. The Fast Fourier Transform (FFT) is a computationally optimized version of the Fourier Transform.

5.3 The Decibel dB Scale

Vibration data is often exhibited in a logarithmic scale called the Decibel (dB) scale. This scale is subsidiary because vibration levels can vary from very small to very large values. When plotting the full data range on most scales, the minute signals become virtually invisible. The dB scale solves this problem because it compresses immensely large numbers and expands minute numbers. A dB value can be computed from a linear value by the equation: where xref is a reference number that depends on the type of quantification.

Vibration Measurements Vibration Sensors Structural vibration is commonly measured with electronic sensors called accelerometers. These sensors convert an acceleration signal to an electronic voltage signal that can then be measured, analyzed and recorded with electronic hardware..

In our experimental activity we are interested in analyzing laser based vibrometer to compare the results with the simulations .

5.4 Laser Doppler vibrometry

Laser Doppler vibrometry is currently the method that offers the best displacement and velocity resolution and is used in many fields of basic science. It enables femtometer amplitude resolution and is linear and therefore has a consistent amplitude right up to the very high frequency ranges – reaching more than 1 GHz at present. These properties are independent of the measuring distance, so this principle is used both in microscopic operations and over very large distances. Light as a sensor does not influence the sample, making it non-invasive and therefore enabling measurements to be carried out on extremely small and extremely lightweight structures.

5.4.1 The doppler effect

If a wave is reflected by a moving object and detected by an instrument (as is the case with the LDV), the quantified frequency shift of the wave can be described as:

$$f_D = 2 \cdot v/\lambda$$

where v is the velocity of sphere surface and λ is the wavelength of the emitted wave. To be able to conversely determine the velocity of an object, the (Doppler) frequency shift has to be quantified at a known wavelength. This is done in the LDV by utilizing a laser interferometer.

5.4.2 Interferometry

The laser Doppler vibrometer works on the substructure of optical interference, whereby essentially two coherent light beams, with their respective light intensities I1 and I2, are required to overlap. The total intensity of both beams is not just the sum of the single intensities, but is modulated according to the formula:

$$Itot = I1 + I2 + 2\sqrt{(I1\ I2)} \cos\left[2\pi(r1 - r2)/\lambda\right]$$

with a so called t “interference” term. This interference term relates to the path length distinction between both beams. If this difference is an integer multiple of the light wavelength, the total intensity is four times a single intensity.

5.4.3 Optical set-up

The beam of a laser is split by a beam splitter (BS 1) into a reference beam and a quantification beam. After passing through a second beam splitter (BS 2), the quantification beam is focused onto the sample, which reflects it. This reflected beam is now deflected downwards by BS 2 (optically discern figure), and is then merged with the reference beam onto the detector.

As the optical path of the reference beam is constant over time (r2 = const.) (with the exception of negligible thermal effects on the interferometer), a movement of the sample (r1 = r(t)) engenders a light / dark pattern, typical of interferometry, on the detector. One complete light / dark cycle on the detector corresponds to an object displacement of precisely a half of the wavelength of the light utilized. In the case of the helium neon laser often utilized for vibrometers, this corresponds to a displacement of 316 nm.

Change in the length of optical path per unit of time manifests itself as the quantification beam's Doppler frequency shift. In metrological terms, this designates that the modulation frequency of the interferometer pattern determined is directly proportional to the velocity of the sample. As object movement away from the interferometer engenders the same modulation pattern (and modulation frequencies) as object movement towards the interferometer, this establishment alone cannot unequivocally determine the direction the object is moving in. For this purpose, an acousto-optic modulator (Bragg cell) that typically shifts the light frequency by 40 MHz is placed in the reference beam (for comparison purposes, the laser light's frequency is 4.74 • 1014 Hz). This engenders a typical interference pattern modulation frequency of 40 MHz when the sample is at a standstill. If the object then moves towards the interferometer, this modulation frequency is incremented, and if it moves away from the interferometer, the detector receives a frequency less than 40 MHz [20]. This means that it is now possible to not only clearly detect the path length, but also the direction of movement additionally.

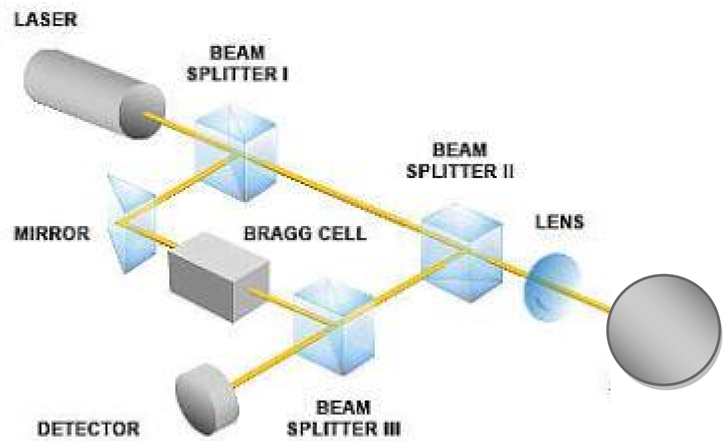


Fig: Schematic diagram to perform NDT on ball bearings

5.4.4 Measuring the displacement/velocity:

In principle, it is possible to directly measure displacements as well as velocities with the LDV. In this case, the Doppler frequency is not transformed into a voltage proportional to velocity; instead, the LDV counts the light / dark fringes on the detector [17].Utilizing opportune interpolation techniques vibrometers can thus procure a resolution of 2 nm, and with digital demodulation techniques this can even be elongated as far down as the pm range.

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