CHAPTER 7

RESULTS AND DISCUSSION
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The theoretical amplitudes of vibrations and its frequency have been calculated by deriving mathematical equations. The theoretical results obtained with respect to speed and defect size have been tabulated in Table 4.5 (Ref Ch. 4). In the numerical study, the model of outer and inner ring deep groove ball bearing has been prepared using ANSYS. The numerical results are obtained by using LS-DYNA solver for similar operating conditions for same speed and defect sizes. The obtained results are tabulated in Table 5.2 (Ref Ch. 5). In order to validate the results obtained by theoretical and numerical study, an experimental set up has been developed. Considering similar operating conditions for experimental work, the amplitudes of vibrations and its frequencies are measured and tabulated in Table 6.5 (Ref Ch.6). The detailed discussion of obtained results is as given below.

7.1 Theoretical Results

For the bearings with outer ring and inner ring defect, the amplitude versus frequency plots are drawn at various speeds ranging from 1000- 5000rpm with defect size 0.25 - 2.0mm and at load ranging from 5 to 25kg. It is observed that as load varies from 5 kg to 25Kg, negligible variations in magnitude of amplitudes of vibration and frequency is noted.
7.1.1 Amplitudes of Vibration for outer ring defected bearings with variations in defect size [Theoretical].

A] At 1000 rpm, Defect size - 0.25mm to 2mm and 5 Kg load

Fig 7.1a depicts amplitude of vibration having peak of 8.20 mm/ s² at 41.63 Hz for defect size of 0.25 mm. For 0.5mm defect size, amplitude of vibration increases to peak of 16.3 mm/ s² at 41.63 Hz which is as shown in Fig 7.1b. As speed is constant to 1000rpm for all the defect sizes, it is observed that the excitation frequency of 41.63 Hz remains unchanged. As the excitation frequency depends upon bearing dimensions and speed of rotation, the change in amplitude is noted with defect size. This effect is highlighted more in case of defect sizes of 1mm and 2mm on outer ring which is as shown in Fig 7.1c and Fig 7.1d respectively. For 1mm and 2mm defect sizes on outer ring, the amplitudes of vibration are 31.7 mm/ s² and 57.1 mm/ s² respectively at 41.63 Hz.

![Graphs showing theoretical amplitudes for different defect sizes](image-url)

Fig 7.1 Theoretical amplitudes at 1000rpm and 5kg load for outer ring defected bearings with defect size of a) 0.25mm b) 0.5mm c) 1.0mm d) 2.0mm
B] At 2000 rpm, Defect size- 0.25mm to 2mm and 5 Kg load

As speed changes from 1000 rpm to 2000 rpm, the excitation frequency shifted from 41.63 Hz to 83.265 Hz for any defect sizes. Fig 7.2a and Fig 7.2b shows, the amplitudes of vibration of test bearing having peak of 33.1 mm/ s² and 65.8 mm/ s² at 83.265 Hz (2000 rpm) for defect size of 0.25 mm and 0.5 mm on outer ring respectively. Similarly, Fig 7.2c depicts amplitudes of vibration having peak of 128 mm/ s² for defect size of 1.0 mm and Fig 7.2d depicts amplitude of vibration having peak of 231 mm/ s² for defect size of 2.0 mm on outer ring of test bearing. From Fig 7.2a to d, it is observed that for 2000 rpm, all the peaks of amplitudes of vibration follows the same trend with respect to defect size as discussed earlier at 1000 rpm. It is also noticed that excitation frequency does not changes with defect size.

Fig 7.2 Theoretical amplitudes at 2000rpm and 5kg load for outer ring defected bearings with defect size of a) 0.25mm b) 0.5mm c) 1.0mm d) 2.0mm
C] At 3000 rpm, Defect size- 0.25mm to 2mm and 5 Kg load

At the speed of 3000 rpm, the corresponding outer ring defect frequency is 124.897 Hz for all defect sizes. As compared to 1000 rpm and 2000 rpm, the excitation frequencies and peak amplitudes at 3000 rpm are higher. Fig 7.3a depicts amplitude of vibration having peak of 75.9 mm/s² at 124.897 Hz for defect size of 0.25 mm. Fig 7.3b shows amplitude of vibration having peak of 151 mm/s² at 124.897 Hz for defect size of 0.5 mm. Similarly, Fig 7.3c depicts amplitudes of vibration having peak of 294 mm/s² at 124.897 Hz for defect size of 1.0 mm and Fig 7.3d depicts amplitude of vibration having peak of 529 mm/s² at 124.897 Hz for defect size of 2.0 mm. It is noted that amplitudes of vibration are far higher in this case than previous cases. This is because acceleration amplitude is function of frequency square (ω²x) and hence amplitude varies with square of excitation frequencies. It is observed that at 3000 rpm, all the peaks of amplitudes of vibration follow the same trend with respect to defect size as like at 1000 rpm and 2000 rpm. It is also noticed that defect size has no any relation with excitation frequency.

Fig 7.3 Theoretical amplitudes at 3000rpm and 5kg load for outer ring defected bearings with defect size of a) 0.25mm b) 0.5mm c) 1.0mm d) 2.0mm
At 5000 rpm, Defect size- 0.25mm to 2mm and 5 Kg load

Further for the speed of 5000 rpm, the corresponding outer ring defect frequency is 208.163 Hz which is as depicted in Fig 7.4 a to 7.4 d. The peaks are observed with amplitudes of 224 mm/s², 444 mm/s², 866 mm/s² and 1710 mm/s² for 0.25 mm, 0.5 mm, 1.0 mm and 2.0 mm defect size respectively on the outer ring of test bearings. It is also observed that in all the four cases mentioned above, the excitation frequency remains constant i.e. 208.163 Hz. It is obvious that amplitudes of vibration are directly proportional to defect sizes and frequency of excitation does not have any effect on the defect sizes. In comparison with 1000rpm, 2000rpm and 3000 rpm, the frequency as well as amplitudes of vibration are higher at 5000 rpm. The reason is already discussed in the previous paragraph.

It is also noticed that at 5000 rpm, all the peaks of amplitudes of vibration follows the same trend with respect to defect size as discussed earlier.

Fig 7.4 Theoretical amplitudes at 5000rpm and 5kg load for outer ring defected bearings with defect size of a) 0.25mm b) 0.5mm c) 1.0mm d) 2.0mm

It is summarized that for the outer ring defected bearings when speed increased from 1000 rpm to 5000 rpm the amplitude of vibration increases from 8.2 mm/s² to 1710 mm/s² for defect size 0.25 mm to 2.0 mm. It is further noticed that increase in load does not play a vital role in variations in amplitudes of vibration and frequency.
7.1.2 Amplitudes of Vibration for inner ring defected bearings with variations in defect size [Theoretical]

A] At 1000 rpm, Defect size 0.25mm to 2mm and 5 Kg load

As discussed in the previous chapter, defect on inner ring rotates along with shaft and not always in the load zone. Hence the peak amplitudes are smaller than outer ring defected bearings for all the defect sizes. But at the same time excitation frequency is higher than outer ring defected bearings as explained in Eq. 4.4 and Eq. 4.5 of Chapter 4. Fig 7.5a to Fig 7.5d shows the peak amplitudes at inner ring defect frequency 75.034 Hz which is excited at constant speed of 1000 rpm. The values of amplitudes of vibration are 5.78 mm/ s², 11.3 mm/ s², 20.8 mm/ s² and 29.4 mm/s² at 0.25 mm, 0.5 mm, 1.0mm and 2.0 mm defect size respectively on inner ring of test bearing. The trend observed in this case is same as that of outer ring defected bearings. The only change is observed in excitation frequency and amplitudes of vibration in this case than outer ring defected bearings. In this case also, frequency has no effect on variations in defect size.

Fig 7.5 Theoretical amplitudes at 1000rpm and 5kg load for inner ring defected bearings with defect size of a) 0.25mm b) 0.5mm c) 1.0mm d) 2.0mm
B) At 2000 rpm, Defect size 0.25mm to 2mm and 5 Kg load

Fig 7.6a to Fig 7.6d depicts the peak amplitudes of vibration at 2000 rpm. In this case inner ring characteristics defect frequency is 150.068 Hz. It is almost double than its value at 1000rpm. The peak amplitudes in this case are 23.9 mm/s², 46.9 mm/s², 86.1 mm/s² and 122 mm/s² at 0.25 mm, 0.5 mm, 1.0mm and 2.0mm defect size on inner ring respectively.

It is noted that, the amplitudes of vibration increases whereas excitation frequency does not change with defect size.

Fig 7.6 Theoretical amplitudes at 2000rpm and 5kg load for inner ring defected bearings with defect size of a) 0.25mm b) 0.5mm c) 1.0mm d) 2.0mm
C] At 3000 rpm, Defect size 0.25mm to 2mm and 5 Kg load

As speed of rotation increases to 3000rpm, the frequency of excitation as well as amplitude of vibration increases drastically. This is because excitation frequency is function of speed. Though the amplitudes of vibration are higher in this case, the values are smaller than outer ring defected bearings for the same speed and defect size. Fig 7.7a illustrates amplitude of vibration having peak of 57.3 mm/s² at 225.102 Hz for defect size of 0.25 mm. Fig 7.7b depicts amplitude of vibration having peak of 112 mm/s² at 225.102 Hz for defect size of 0.5 mm. Similarly, Fig 7.7c and Fig 7.7d depicts amplitudes of vibration having peak of 206 mm/s² and 291 mm/s² at 225.102 Hz for defect size of 1.0 mm and 2.0 mm on inner ring of bearing respectively. From Fig 7.7 a to d, it is observed that at 3000 rpm, all the peaks of amplitudes of vibration follow the same trend with respect to defect size as discussed earlier. It is also noticed that excitation frequency does not change with defect sizes.

**Fig 7.7** Theoretical amplitudes at 3000rpm and 5kg load for inner ring defected bearings with defect size of a) 0.25mm b) 0.5mm c) 1.0mm d) 2.0mm
D) At 5000 rpm, Defect size 0.25mm to 2mm and 5 Kg load

Fig 7.8a to Fig 7.8d plotted for amplitude versus frequency of inner ring defected bearings at 5000 rpm with defect size ranging from 0.25 to 2.0mm. The inner ring defect frequency excited in this case is 375.1708 Hz which is highest in all the cases. The peaks observed in this case are of magnitude 199 mm/s², 391 mm/s², 717 mm/s² and 1010 mm/s², respectively for 0.25mm, 0.5mm, 1.0mm and 2.0mm defect size defect size on inner ring. It is clearly noted that inner ring defected bearings are showing lower values of amplitudes than outer ring defected bearings for the same defect size. From Fig7.8 a to d, it is observed that at 5000 rpm, all the peaks of amplitudes of vibration follows the same trend with respect to defect size as discussed earlier. It is also noticed that variation in defect size does not affect the excitation frequency.

![Fig 7.8 Theoretical amplitudes at 5000rpm and 5kg load for inner ring defected bearings with defect size of a) 0.25mm b) 0.5mm c) 1.0mm d) 2.0mm](image)

It is summarized that for the inner ring defected bearings when speed increased from 1000 rpm to 5000 rpm the amplitude of vibration increases from 5.78 mm/s² to 1010 mm/s² for defect size 0.25 mm to 2.0 mm. It is further noticed that increase in load does not play a vital role in variations in amplitudes of vibration and frequency. There is insignificant change in amplitudes of vibrations and frequencies with load for any speed and defect size.
7.2 Numerical Results using ANSYS/LS-DYNA

The model has been prepared for both outer ring and inner ring defected bearings. Separate meshing is used for each bearing elements. When defect is on outer ring, Tetrahedron (Solid 168) meshing (free) is used for outer ring and balls. This meshing is preferably suitable for irregular and complicated parts. In this case as there is no defect on inner ring therefore Hexahedron (Solid 164) meshing (mapped) is preferred. Whereas for inner ring defected bearings, Tetrahedron meshing (Free) is incorporated for inner ring and Hexahedron meshing (mapped) is used for Outer ring. By simulating all the parameters, the detailed discussion of obtained results is as given below. To obtain the results of inner ring defected bearings using ANSYS/LS-DYNA is very intricate process because defect on inner ring is rotating. Even though, approximated results obtained by this method are close to theoretically obtained results.
7.2.1 Amplitudes of Vibration for Outer ring defected bearings with variations in defect size [Numerical]

A] At 1000 rpm, Defect size 0.25mm to 2mm and 5 Kg load

The excitation frequency of outer ring defected bearing \((f_0)\) is 41 Hz at 1000 rpm and remains same for all the defect sizes. It is as shown in Fig 7.9a to Fig 7.9d. The peak amplitudes of vibration of 10.9 mm/ s\(^2\), 16.2 mm/ s\(^2\), 29.4 mm/ s\(^2\) and 59.4 mm/ s\(^2\) are observed for defect size from 0.25mm, 0.5mm, 1.0mm and 2.0mm respectively. Thus it is noted that all the peaks of amplitudes of vibration increases with increase in defect size and frequency has no effect on defect sizes.

![Frequency domain plots (Using ANSYS/LSDYNA) at 1000 rpm for bearing with outer ring defect size a) 0.25mm b) 0.5mm c) 1.0mm d) 2.0mm](image-url)
B] At 2000 rpm, Defect size 0.25mm to 2mm and 5 Kg load

With increase in the speed up to 2000 rpm, characteristics defect frequency (f₀) is shifted from 41 Hz to 84 Hz which is almost double of previous case. Fig 7.10a depicts amplitude of vibration having peak of 40.3 mm/s² at 84 Hz for defect size of 0.25 mm and Fig 7.10b depicts amplitude of vibration having peak of 70.3 mm/s² at 84 Hz for defect size of 0.5 mm. Similarly Fig 7.10c and Fig 7.10d show amplitudes of vibration having peak of 124 mm/s² and 240 mm/s² at 84 Hz for defect size of 1.0 mm and 2.0 mm respectively on the outer ring of bearing. It is noted that amplitudes of vibration and corresponding frequency are higher at 2000 rpm than at 1000 rpm for any size of defect. Frequency remains constant for any defect size whereas amplitude is directly proportional to defect size.

![Fig 7.10: Frequency domain plots (Using ANSYS/LSDYNA) at 2000 rpm for bearing with outer ring defect size a) 0.25mm b) 0.5mm c) 1.0mm d) 2.0mm](image-url)
At 3000 rpm, Defect size 0.25mm to 2mm and 5 Kg load

As excitation frequency is function of speed, its value increases from 84 Hz (at 2000 rpm) to 126 Hz at 3000 rpm. As LS-DYNA is preferred for short duration phenomenon, the results obtained are close to theoretical results for the same speed and different defect sizes. The amplitude of vibration having peak of 72.4 mm/s² is observed in Fig 7.11a at 126 Hz for defect size of 0.25 mm. When defect size increases, the same frequency is excited but with increase in the level of amplitude. Fig 7.11b shows amplitude of vibration having peak of 157 mm/s² at 126 Hz for defect size of 0.5 mm. Similarly, Fig 7.11c and Fig 7.11d depicts amplitude of vibration having peak of 289 mm/s² and 550 mm/s² at 126 Hz for defect size of 1.0 mm and 2.0 mm respectively on the outer ring of bearing. Hence, From Fig7.11 a to d, it is observed that at 3000 rpm, all the peaks of amplitudes of vibration increase with increase in defect size. These values of amplitudes are higher than earlier case at 1000 and 2000 rpm for the same defect size. It is also noticed that excitation frequency does not change with defect size.

Fig7.11: Frequency domain plots (Using ANSYS/LSDYNA) at 3000 rpm for bearing with outer ring defect size a) 0.25mm b) 0.5mm c) 1.0mm d) 2.0mm
D] At 5000 rpm, Defect size 0.25mm to 2mm and 5 Kg load

At speed of 5000 rpm, the ball pass frequency of outer race \( (f_o) \) i.e. characteristics defect frequency of outer race is obtained as 210 Hz. This is slightly deviated by 2Hz than theoretically calculated defect frequency because of complexity of meshing of bearing system at higher speed. Fig 7.12a to Fig 7.12d depicts amplitudes of vibration having peak of 234 mm/s\(^2\), 454 mm/s\(^2\), 905 mm/s\(^2\) and 1740 mm/s\(^2\) at 210 Hz for defect size of 0.25 mm, 0.5mm, 1.0mm and 2.0 mm respectively. The levels of amplitudes are higher than the earlier case at 1000 rpm to 3000 rpm. In this case also, it is proved that there is no any effect of defect size on the excitation frequency. From Fig7.12 a to d, it is observed that at 5000 rpm, all the peaks of amplitudes of vibration increase with increase in defect size.

Fig 7.12: Frequency domain plots (Using ANSYS/LSDYNA) at 5000 rpm for bearing with outer ring defect size a) 0.25mm b) 0.5mm c) 1.0mm d) 2.0mm

It is summarized that for the outer ring defected bearings when speed increased from 1000 rpm to 5000 rpm the amplitude of vibration increases from 10.90 mm/s\(^2\) to 1740 mm/s\(^2\) for defect size 0.25 mm to 2.0 mm. It is further noticed that increase in load does not play vital role in variations in amplitudes of vibration and frequency.
7.2.2 Amplitudes of Vibration for inner ring defected bearings with variations in defect size [Numerical].

A] At 1000 rpm, Defect size 0.25mm to 2mm and 5 Kg load

For inner ring defected bearings, ball pass frequency of inner race ($f_i$) is excited which is as shown in Fig 7.13a to Fig 7.13d. In this case for 1000 rpm, the peak amplitudes of vibration are obtained at 77 Hz. With variation in defect size from 0.25mm to 2.0 mm, the amplitude levels are in the range of 8.45 mm/s$^2$ to 33.5 mm/s$^2$ at the same defect frequency ($f_i$) that is 77 Hz. The excitation frequency in this case is higher than outer ring defected bearings (Ref Eq. 4.5) but amplitude of vibration is always smaller than amplitudes of vibration of outer ring defected bearings because in latter case defect is stationary as discussed earlier. Hence from Fig7.13 a to d, it is observed that at 1000 rpm, all the peaks of amplitudes of vibration increases with increase in defect size and defect size does not affect the excitation frequency.

![Frequency domain plots](image)

Fig7.13: Frequency domain plots (Using ANSYS/LSDYNA) at 1000 rpm for bearing with inner ring defect size a) 0.25mm b) 0.5mm c) 1.0mm d) 2.0mm
B) At 2000 rpm, Defect size 0.25mm to 2mm and 5 Kg load

In case of 2000 rpm, the characteristics defect frequency due to defect on inner ring (f1) increases to 151 Hz as speed has direct effect on the excitation frequency. Fig 7.14a depicts amplitude of vibration having peak of 24.2 mm/s² at 151 Hz for defect size of 0.25 mm and Fig 7.14b shows amplitude of vibration having peak of 45.2 mm/s² at 151 Hz for defect size of 0.5 mm. With further increase in size of defect, the levels of amplitude increase which are obtained at same frequency i.e. 151Hz. Fig 7.14c and Fig 7.14d depicts amplitude of vibration having peak of 107 mm/s² and 117 mm/s² at 151 Hz for defect size of 1.0 mm and 2.0mm, respectively. In case of inner ring defected bearings with 2.0mm defect, numerical results have not given good response at 2000 rpm because amplitude level is not increased much than amplitude level at 1mm defect size. Further it is noticed that defect frequency has no effect on variations in defect size.

Fig7.14: Frequency domain plots (Using ANSYS/LSDYNA) at 2000 rpm for bearing with inner ring defect size a) 0.25mm b) 0.5mm c) 1.0mm d) 2.0mm
C] At 3000 rpm, Defect size 0.25mm to 2mm and 5 Kg load

The excitation frequency in this case is 229 Hz which is characteristics defect frequency of inner ring ($f_i$). Fig 7.15a illustrates amplitude of vibration having peak of 81.4 mm/s^2 at 229 Hz for defect size of 0.25 mm and Fig 7.15b depicts amplitude of vibration having peak of 129 mm/s^2 at 229 Hz for defect size of 0.5 mm. Similarly, Fig 7.15c depicts amplitude of vibration having peak of 199 mm/s^2 and Fig 7.15d depicts amplitude of vibration having peak of 301 mm/s^2 at 229 Hz for defect size of 1.0 mm and 2.0 mm respectively on the inner ring of bearing. In this case also frequency has no effect on variations in defect size. From Fig 7.15a to d, it is observed that at 3000 rpm, all the peaks of amplitudes of vibration increases with increase in defect size.

![Frequency domain plots (Using ANSYS/LSDYNA) at 3000 rpm for bearing with inner ring defect size a) 0.25mm b) 0.5mm c) 1.0mm d) 2.0mm](image)
D) At 5000 rpm, Defect size 0.25mm to 2mm and 5 Kg load

At 5000 rpm, the corresponding inner ring defect frequency ($f_l$) is 378 Hz which is as depicted in Fig 7.16 a to 7.16 d. In this case, the defect frequency is deviated by 3Hz than theoretically calculated defect frequency. This is due to complexity of meshing of bearing system. Fig 7.16a to Fig 7.16d depicts amplitudes of vibration having peak of 196 mm/ s², 428 mm/ s², 693 mm/ s² and 1040 mm/ s² at 378 Hz for defect size of 0.25 mm, 0.5mm, 1.0mm and 2.0 mm respectively. The amplitude levels are higher than the earlier case at 1000 rpm to 3000 rpm. In this case also it is proved that there is no any effect of defect size on the excitation frequency. From Fig7.16 a to d, it is observed that at 5000 rpm, all the peaks of amplitudes of vibration increased with increase in defect size.

![Fig 7.16: Frequency domain plots (Using ANSYS/LSDYNA) at 5000 rpm for bearing with inner ring defect size a) 0.25mm b) 0.5mm c) 1.0mm d) 2.0mm](image)

It is summarized that for the inner ring defected bearings when speed increases from 1000 rpm to 5000 rpm the amplitude of vibration increases from 8.45 mm/s² to 1040 mm/s² for defect size 0.25 mm to 2.0 mm. It is further noticed that increase in load does not plays vital role in variations in amplitudes of vibration and frequency.
7.2.3 Time domain approach

The numerical work has also been extended for time domain analysis for various defect sizes and speeds. Fig 7.17a to d depicts amplitude versus time plot for bearing with 1mm defect on outer ring and the peaks are observed at period of reciprocal of outer ring defect frequency (i.e. $1/f_o$). The impulses obtained are at period of 0.0244 sec, 0.01190 sec, 0.0079 sec and at 0.00476 sec at 1000, 2000, 3000 and 5000 rpm respectively which are shown in Fig 7.17a to Fig 7.17d. These periods are corresponding to frequencies of 41Hz, 84Hz, 126Hz and 210Hz at respective speeds.

It is observed that with increase in rpm, overall amplitudes of vibration and frequency of excitation also increases.

Fig 7.17a: Time domain plot for bearing with 1mm defect on outer ring at 1000rpm (Using ANSYS)

Fig 7.17b: Time domain plot for bearing with 1mm defect on outer ring at 2000rpm (Using ANSYS)
Similarly, Fig 7.18a to d depicts amplitude versus time plot for bearing with 1mm defect on inner ring and the peaks are observed at period of reciprocal of inner ring defect frequency (i.e. $1/f_i$). These frequencies are 77Hz, 151Hz, 229Hz and 378Hz at 1000 rpm, 2000 rpm, 3000 rpm and 5000 rpm respectively which are reciprocals of period 0.0129 sec, 0.0066 sec, 0.0043 sec and 0.0026 sec at respective speeds.

It is observed that with increase in rpm overall amplitudes of vibration and excitation frequency also increase.
Fig 7.18a: Time domain plot for bearing with 1mm defect on inner ring at 1000rpm (Using ANSYS).

Fig 7.18b: Time domain plot for bearing with 1mm defect on inner ring at 2000rpm (Using ANSYS).
It is summarized that in time domain analysis, with 1mm defect size and for different speeds, the magnitude of amplitudes of vibrations for outer ring defected bearing is almost double than inner ring defected bearing. As bearing is very complex part, perfect modeling and meshing of all elements becomes difficult. Hence slight variation of 1Hz to 3Hz is observed in the defect frequencies. This effect is common for all defect sizes and all speeds.
7.3 Experimental Results

The detail description of experimental set up is explained in Chapter 6. In the experimental set up, simply supported arrangement is used. Initially, bearing with no defect on bearing elements (Healthy Bearing) is used as a test bearing and amplitudes of vibrations are measured for different speeds and loading conditions. The results obtained with healthy bearings are referred as standards of amplitudes of vibration and frequencies. Fig 7.19a to d depicts effect of variations in speed on amplitudes of vibration and its frequency for healthy bearing. At 1000 rpm, amplitude of vibration of magnitude 4 mm/s$^2$ at outer ring defect frequency (42 Hz) and 3 mm/s$^2$ at inner ring defect frequency (75 Hz), are observed. At 2000 rpm, amplitude of vibration of magnitude 20 mm/s$^2$ at outer ring defect frequency (83 Hz) and 15 mm/s$^2$ at inner ring defect frequency (150 Hz), are observed. At 3000 rpm, amplitude of vibration of magnitude 17 mm/s$^2$ at outer ring defect frequency (124 Hz) and 25 mm/s$^2$ at inner ring defect frequency (224 Hz), are observed and at 5000 rpm, amplitude of vibration of magnitude 30 mm/s$^2$ at outer ring defect frequency (208 Hz) and 20 mm/s$^2$ at inner ring defect frequency (378 Hz), are observed. Time domain plots of healthy bearings at different speeds is as shown in Fig 7.20 a to d. Overall amplitude level increases which is as shown in Figure.

It is summarized that for healthy bearing also amplitude of vibration and its frequency increases with increase in speed.

![Fig 7.19a:- Acceleration vs frequency for healthy bearing at 1000rpm and 5kg load.](image)
Fig 7.19b:- Acceleration vs frequency for healthy bearing at 2000rpm and 5kg load.

Fig 7.19c:- Acceleration vs frequency for healthy bearing at 3000rpm and 5kg load.

Fig 7.19d:- Acceleration vs frequency for healthy bearing at 5000rpm and 5kg load.
7.3.1. Amplitudes of Vibration for Outer ring defected bearings with variations in defect size [Experimental]

A] At 1000 rpm, Defect size - 0.25mm to 2mm and 5 Kg load

Fig 7.21a shows the acceleration amplitudes of outer ring defected bearing at 1000rpm and 5kg load with defect width of 0.25mm on outer ring. Peaks at shaft rotation frequency \((f_s=16.66\text{Hz})\) and outer ring defect frequency \((f_o=42\text{Hz})\) are highlighted. At the same time some harmonic peaks such as \(2f_o, 3f_o\) are also noted. When defect size
increases at constant speed and load, same frequencies are excited with increase in the level of vibration amplitudes. This effect is shown in Fig 7.21b to Fig 7.21d. In case of Fig 7.21c, harmonic peaks are not observed whereas Fig 7.21d shows clear harmonic peaks even at $4f_0$, $6f_0$, $7f_0$ etc. The amplitude levels of 10 mm/s$^2$, 18.4 mm/s$^2$, 34.2 mm/s$^2$ and 63.4 mm/s$^2$ at 42 Hz are as shown in Fig 7.21a to Fig 7.21d. From Fig 7.21a to d, it is observed that at 1000 rpm, all the peaks of amplitudes of vibration increase with increase in defect size whereas frequency remains unchanged with defect size. The harmonic frequencies of $2f_0$, $3f_0$ and $4f_0$ are also observed at same speed.

Fig 7.21a: Amplitudes of test bearing at 1000rpm, 5kg load with defect width of 0.25mm on outer ring.

Fig 7.21b: Amplitudes of test bearing at 1000rpm, 5kg load with defect width of 0.5mm on outer ring.
B) At 2000 rpm, Defect size - 0.25mm to 2mm and 5 Kg load

When speed of rotation increases to 2000rpm, excited outer ring defect frequency \( f_0 \) is 83Hz. This effect is observed in Fig 7.22a to Fig 7.22d. Amplitudes of test bearing at 2000rpm & 5kg load with defect width of 0.25 mm on outer ring is as depicted in Fig 7.22a. Graph shows peaks at shaft rotation frequency \( f_s = 33.33 \text{Hz} \) and outer ring defect frequency \( f_0 = 83 \text{Hz} \). Some harmonic peaks at \( 2f_0, 3f_0 \) are also noted. In case of larger defect size, vibration levels are more at same defect frequency. It is observed in Fig 7.22b to Fig 7.22d. Bearing with 1mm defect on outer ring gives very good response at 2000rpm. Acceleration versus frequency plot for this case is depicted in Fig 7.22c. It shows harmonic peaks at \( 2f_0, 3f_0 \) and \( 4f_0 \) respectively. The peaks of amplitude 37.2 mm/ \( s^2 \), 74.5 mm/ \( s^2 \), 143 mm/ \( s^2 \) and 252 mm/ \( s^2 \) are clearly depicted at outer ring defect frequency \( f_0 \) 83 Hz in Fig 7.22a to d.
Fig 7.22a: Amplitudes of test bearing at 2000rpm, 5kg load with defect width of 0.25mm on outer ring.

Fig 7.22b: Amplitudes of test bearing at 2000rpm, 5kg load with defect width of 0.5 mm on outer ring.

Fig 7.22c: Amplitudes of test bearing at 2000rpm, 5kg load with defect width of 1.0 mm on outer ring.
C] At 3000 rpm, Defect size - 0.25mm to 2mm and 5 Kg load

Increase in level of amplitudes of vibration is noted at 125Hz defect frequency for corresponding speed of 3000 rpm which is as shown in Fig 7.23. In addition with harmonic peaks of outer ring defected frequency (2fo, 3fo etc), some other peaks such as fo+fs, fo-fs are also observed in this case. These peaks are observed in Fig 7.23a where frequencies 75Hz and 175Hz are excited corresponding to fo- fs and fo + fs respectively. In case of 0.5mm defect size, amplitude levels are increased as depicted in Fig 7.23b. Here also harmonic peaks are obtained at fo+fs and fo-fs. Fig 7.23c and Fig 7.23d shows the peaks at 125Hz, 250Hz, 375Hz and 500Hz corresponding to fo, 2fo, 3fo and 4fo respectively. These two graphs are corresponding to the defect size of 1.0mm and 2.0mm on outer ring of test bearing respectively. In case of Fig 7.23d, fo + fs and fo- fs peaks are clearly observed. The range of amplitude levels in this case is from 88.4 mm/ s² to 564 mm/ s² at 125.23 Hz for defect size of 0.25mm to 2.0mm.
Fig 7.23b: Amplitudes of test bearing at 3000rpm, 5kg load with defect width of 0.5 mm on outer ring.

Fig 7.23c: Amplitudes of test bearing at 3000rpm, 5kg load with defect width of 1.0 mm on outer ring.

Fig 7.23d: Amplitudes of test bearing at 3000rpm, 5kg load with defect width of 2.0 mm on outer ring.
D) At 5000 rpm, Defect size - 0.25mm to 2mm and 5 Kg load

When speed increases to 5000rpm, the peaks are obtained at outer ring defect frequency (fo), 208Hz and its harmonics. Fig 7.24a shows acceleration amplitude of 250 mm/ s² for 0.25mm defect on outer ring at 208 Hz and also shows other peaks at fs and 2fo. In case of bearing with 0.5mm defect on outer ring, additional peaks at fo + fs and fo- fs are also noted as shown in Fig 7.24b. Bearing with 1.0mm defect on outer ring gives number of peaks at various frequencies as explained in Fig 7.24c. Due to increased speed and large size of defect, some increase in noise level is observed. The number of peaks noted are at frequencies fo, 2fo, 3fo, 4fo, fs, 2fs, fo+fs, fo- fs, 2fo+fs, 2fo+2fs, 2fo-fs etc. When the size of defect increase to 2.0mm, amplitude levels are further increased to higher value. In this case also number of harmonic peaks at fo, 2fo, fo+fs, fo-fs, 2fo+fs, 2fo-fs are clearly observed as given in Fig 7.24d. The amplitude of vibration of 1840 mm/ s² is obtained at 208Hz frequency for the defect size of 2.0mm on outer ring. From Fig 7.24 a to d, it is observed that for 5000 rpm, all the peaks of amplitudes of vibration increases with increase in defect size. Further it is noticed that frequency has no effect on variations in defect size.
The comparison of amplitudes of vibrations at variations in a) speed b) defect size and c) load has been made and plotted as shown in Fig 7.25a, Fig 7.25b and Fig 7.25c respectively. Fig 7.25c depicts that there is no far variation in the amplitudes of vibration with respect to load for outer ring defected bearing with first defect size 0.25mm (od1) to last defect size 2.0mm (od4) at any speed. Amplitudes of vibration of healthy bearings are also given in the figures for the comparison. It is noted that the amplitudes of healthy bearings are in the range of 4 to 30 mm/s^2 for the speed range of 1000 rpm to 5000 rpm where as for the outer ring defected bearings the range of amplitudes is from 10 to 1840 mm/s^2 for the same range of speed. It is observed that the amplitudes of vibration are increased with increase in speed and defect sizes but it has negligible effect with variations in load.
Fig 7.25a: Amplitude Vs Speed for bearing with various defect widths on outer ring & at 5kg load.

Fig 7.25b: Amplitude Vs defect size for outer ring defected bearing at various speeds & at 5kg load.

Fig 7.25c: Amplitude Vs Load for bearing with various defect widths on outer ring & at 5000rpm.
In experimental study, further analysis has been carried out by changing the position of defect at outer ring. Outer ring of bearing is fixed in the housing, and inner ring is revolving with shaft speed. Thus when defect is on outer ring of bearing, it is stationary with respect to shaft. Outer ring of bearing is so mounted in the housing that defect is always located at the maximum position in the load zone because at maximum load position, force of excitation is maximum. When defect position is deviating from maximum position in load zone, force of excitation not only goes on reducing but almost become zero outside the load zone. Thus theoretical amplitudes becomes almost zero if defect is outside load zone, but practically it always shows some negligible non zero values of amplitudes. Fig 7.26a depicts plot of amplitude of vibration versus frequency at 0° defect position (maximum position in load zone) on outer ring. The peak of amplitude 916 mm/s² is observed at 208 Hz. Fig 7.26b depicts plot of amplitude of vibration versus frequency at defect position 10° from maximum position in load zone. The peak of amplitude of vibration of 520 mm/s² is observed at 208 Hz. Fig 7.26c depicts plot of amplitude of vibration versus frequency at defect position 15° from maximum position in load zone. This position is extreme of load zone as calculated theoretically. Even the peak of amplitude of vibration of 170 mm/s² is observed at 208 Hz for this defect position. Fig 7.26d depicts plot of amplitude of vibration versus frequency at defect position 30° from maximum position in load zone. The peak of amplitude of vibration of 60 mm/s² is observed at 208 Hz. It is summarized that, the defect position at the outer ring has significant effect on the peaks of amplitudes of vibration. It is observed that maximum amplitude of vibration is obtained at 0° position in the load zone and it decreases when position of defect shifted from 0° to 30°. During the experimentation, some non zero amplitudes even outside the load zone are observed which may be due to influence of other source of vibrations in the set up at higher speed.

![Fig 7.26a:- Amplitude vs Frequency for bearing with 1mm defect on outer ring at 0° from maximum load position at 5000rpm and 5kg load.](image-url)
In the experimental set up, one of the support bearings is replaced with outer ring defected bearing and efforts has been carried out for measurement of amplitudes of vibrations of test bearing. It is observed that, some kind of random vibrations are observed which may be due to misalignment in the arrangement. Refer Fig 7.27 a to d.
Fig 7.27: Amplitudes of vibrations of Test bearing with defect of 1mm on outer ring at 5000 rpm and 5 kg load when a) Both Support bearings are Healthy b) Right support bearing with 0.25mm defect on Outer ring c) Right support bearing with 0.5mm defect on Outer ring d) Right support bearing with 2.0mm defect on Outer ring.

7.3.2. Amplitudes of Vibration for inner ring defected bearings with variations in defect size [Experimental]

A] At 1000 rpm, Defect size 0.25mm to 2mm and 5 Kg load
If defect is on the inner ring, it also rotates and continuously moves through inside and outside the load zone. The peaks in this case are observed at ball pass frequency of
inner ring \((f_i)\) and its harmonics. Amplitude versus frequency plots for various defect sizes on inner ring at different speeds and loads are plotted. Fig 7.28a depicts amplitude of vibration having peak of 7.32 mm/\(s^2\) at 76.19 Hz for defect size of 0.25 mm. Fig 7.28b depicts amplitude of vibration having peak of 13.5 mm/\(s^2\) at 76.19 Hz for defect size of 0.5 mm.

![Amplitudes of test bearing at 1000 rpm, 5kg load with defect width of 0.25mm on inner ring.](image1)

![Amplitudes of test bearing at 1000 rpm, 5kg load with defect width of 0.5mm on inner ring.](image2)

Similarly, Fig 7.28c and Fig 7.28d depict amplitude of vibration having peak of 23.5 mm/\(s^2\) and 34 mm/\(s^2\) at 76.19 Hz for defect size of 1.0 mm and 2.0 mm respectively on inner ring. From Fig 7.28a to d, it is observed that for 1000 rpm, all the peaks of amplitudes of vibration increases with increase in defect size. Further it is noticed that frequency has no effect on variations in defect size. The harmonic frequencies of 2\(f_i\), 3\(f_i\) and 4\(f_i\) are also observed at same speed.
At 2000 rpm, Defect size 0.25mm to 2mm and 5 Kg load

Fig 7.29a to Fig 7.29d are plotted for inner ring defected bearings at 2000rpm for various defect sizes. Peaks are obtained at $f_s=33.33\text{Hz}$ and $f_i=150\text{Hz}$ for all the defect sizes. Increase in the amplitude level with defect size is clearly noted. Fig 7.29b shows additional peak at $f_i+f_s$ whereas Fig 7.29c shows peaks at $f_i+f_s$, $2f_s$, and $2f_i$. Two strong peaks at shaft rotation frequency ($f_s$) and inner ring defect frequency ($f_i$) are also depicted in Fig 7.29d. Maximum level of amplitude is noted in this case due to larger defect size. The amplitudes of 29 mm$^2$/s$^2$, 54.5 mm$^2$/s$^2$, 96.1 mm$^2$/s$^2$ and 138 mm$^2$/s$^2$ are observed at 150 Hz for defect size of 0.25mm, 0.5mm, 1.0mm and 2.0mm respectively.
Fig 7.29a: Amplitudes of test bearing at 2000rpm, 5kg load with defect width of 0.25mm on inner ring.

Fig 7.29b: Amplitudes of test bearing at 2000rpm, 5kg load with defect width of 0.5mm on inner ring.

Fig 7.29c: Amplitudes of test bearing at 2000rpm, 5kg load with defect width of 1.0mm on inner ring.
C) At 3000 rpm, Defect size 0.25mm to 2mm and 5 Kg load

Fig 7.30a depicts amplitude of vibration having peak of 67.3 mm/ s² at inner ring defect frequency ($f_i$) 227 Hz for defect size of 0.25 mm and Fig 7.30b depicts amplitude of vibration having peak of 133 mm/ s² at 227 Hz for defect size of 0.5 mm. Similarly Fig 7.30c depicts amplitude of vibration having peak of 224 mm/ s² at 227 Hz for defect size of 1.0 mm and Fig 7.30d depicts amplitude of vibration having peak of 322 mm/ s² at 227 Hz for defect size of 2.0 mm. From Fig 7.30a to d, it is observed that for 3000 rpm, all the peaks of amplitude of vibration increase with increase in defect size. Further it is noticed that frequency has no effect on variations in defect size. The harmonic frequencies of $2\omega_0$ and $3\omega_0$ are also observed at same speed.
Fig 7.30b: Amplitudes of test bearing at 3000rpm, 5kg load with defect width of 0.5mm on inner ring.

Fig 7.30c: Amplitudes of test bearing at 3000rpm, 5kg load with defect width of 1.0mm on inner ring.

Fig 7.30d: Amplitudes of test bearing at 3000rpm, 5kg load with defect width of 2.0mm on inner ring.
D] At 5000 rpm, Defect size 0.25mm to 2mm and 5 Kg load

Acceleration amplitudes at speed of 5000rpm with various defect sizes on inner ring are as depicted in Fig 7.31a to Fig 7.31d. The corresponding characteristics defect frequency in this case is 375Hz. Fig 7.31a shows peaks at $f_s$, $f_i$ whereas Fig 7.31b shows peaks at $f_s$, $2f_s$, $f_i$ etc. Two strong peaks at $f_s$ and $f_i$ are observed in Fig 7.31c and Fig 7.31d. Hence in case of inner ring defected bearings, ball pass frequency due to inner ring ($f_i$) is excited at corresponding speed. For constant defect size, amplitude of vibration at respective defect frequencies increases with speed and for constant speed amplitude of vibration increases with defect size. The values of amplitudes of vibration at 0.25mm, 0.5mm, 1.0mm and 2.0mm defect size are 235 mm/ s$^2$, 454 mm/ s$^2$, 739 mm/ s$^2$ and 1090 mm/ s$^2$ respectively at inner ring defect frequency ($f_i$) 375Hz.

![Fig 7.31a](image1.png)

Fig 7.31a: Amplitudes of test bearing at 5000rpm & 5kg load with defect width of 0.25mm on inner ring.

![Fig 7.31b](image2.png)

Fig 7.31b: Amplitudes of test bearing at 5000rpm & 5kg load with defect width of 0.5mm on inner ring.
The comparison of amplitudes of vibrations at variations in a) speed b) defect size and c) load has been made and plotted as shown in Fig 7.32a, Fig7.32b and Fig7.32c respectively. It is observed that the amplitudes of vibration are increased with increase in speed and defect sizes but it has negligible effect with variations in load. Fig 7.32c depicts that there is no far variation in the amplitudes of vibration with respect to load for inner ring defected bearing with first defect size 0.25mm (id1) to last defect size 2.0mm (id4) at any speed. Amplitudes of vibration of healthy bearings are also given in the figures for the comparison. It is noted that the amplitudes of healthy bearings are in the range of 3 to 20 mm/s² for the speed range of 1000 rpm to 5000 rpm where as for the inner ring defected bearings the range of amplitudes is from 7.35 to 1090 mm/s² for the same range of speed. It is observed that the amplitudes of vibration are increased with increase in speed and defect sizes but it has negligible effect with variations in load.
Fig 7.32a: Amplitude Vs Speed for bearing with various defect widths on inner ring & at 5kg load.

Fig 7.32b: Amplitude Vs defect size for inner ring defected bearing at various speeds & at 5kg load.

Fig 7.32c: Amplitude Vs Load for bearing with various defect widths on inner ring & at 5000rpm.
7.3.3 Time domain approach

The Experimental work has also been extended for time domain analysis for various
defect sizes and speeds. Fig 7.33a to d depicts amplitude versus time plot for bearing
with 1mm defect on outer ring and the peaks are observed at period of reciprocal of
outer ring defect frequency (i.e. $1/fo$). The impulses are shown in Figures 7.33 a to d
at period of 0.024 s, 0.012 s, 0.008 s and 0.0048 s for speed of 1000, 2000, 3000 and
5000 rpm respectively. Hence the corresponding frequencies are 42Hz, 83Hz, 125Hz
and 208Hz at respective speed.

Fig 7.33a: Amplitudes vs Time for test bearing at 1000rpm, 5kg load with 1mm defect on outer ring

Fig 7.33b: Amplitudes vs Time for test bearing at 2000rpm ,5kg load with 1mm defect on outer ring
In case of Fig 7.34a to Fig 7.34d, the impulses are obtained at 0.0048 seconds but at different levels of amplitudes. This is because severity of defect increases from 0.25 mm to 2.0 mm at constant speed. It is observed that with increase in rpm, overall amplitudes of vibration and frequency of excitation also increases. For the constant speed, the impulses are obtained at same time period and the level of vibration increases with increase in defect size as shown in Fig 7.34a to d.

Thus time domain analysis gives clear idea that when impulses are obtained at interval of reciprocal of outer ring defect frequency, defect is on the outer ring of test bearing and severity of defect can obtained by its amplitude levels.
Fig 7.34a: Amplitudes vs Time for test bearing at 5000rpm, 5kg load with 0.25mm defect on outer ring.

Fig 7.34b: Amplitudes vs Time for test bearing at 5000rpm, 5kg load with 0.5mm defect on outer ring.

Fig 7.34c: Amplitudes vs Time for test bearing at 5000rpm, 5kg load with 1mm defect on outer ring.
Fig 7.34d: Amplitudes vs Time for test bearing at 5000rpm, 5kg load with 2mm defect on outer ring.

Similarly, in case of inner ring defected bearings, pulses are obtained at time interval which is corresponding to reciprocal of inner ring defect frequencies ($1/f_i$). This time interval for impulses is as low as 0.00267sec for maximum speed of 5000rpm. Acceleration versus time plot for 1mm defect on inner ring at various speeds is as explained in Fig 7.35a to Fig 7.35d. For 1000rpm the impulses are obtained at interval of 0.0133sec whereas they are obtained at 0.0067sec for 2000rpm. Increase in the vibration amplitudes is clearly noted for higher speed. As depicted in Fig 7.35c, peaks are obtained at interval of 0.0044sec for 3000rpm. The corresponding inner ring defect frequencies are 76Hz, 149.5Hz, 227Hz and 374.5Hz at 1000 rpm, 2000 rpm, 3000 rpm and 5000 rpm respectively. It is observed that with increase in rpm overall amplitudes of vibration and excitation frequency also increase.

Fig 7.35a: Amplitudes vs Time for test bearing at 1000rpm, 5kg load with 1mm defect on inner ring.
Fig 7.35b: Amplitudes vs Time for test bearing at 2000rpm, 5kg load with 1mm defect on inner ring

Fig 7.35c: Amplitudes vs Time for test bearing at 3000rpm, 5kg load with 1mm defect on inner ring

Fig 7.35d: Amplitudes vs Time for test bearing at 5000rpm, 5kg load with 1mm defect on inner ring

For the constant speed, the impulses are obtained at same time period and the level of vibration increases with increase in defect size as shown in Fig 7.36a to d. Thus when impulses are obtained at reciprocal of inner ring defect frequencies, the defect is present on inner ring of bearing and its severity can be obtained by severity of amplitude levels at respective speeds.
Fig 7.36a: Amplitudes vs Time for bearing at 5000rpm, 5kg load with 0.25mm defect on inner ring.

Fig 7.36b: Amplitudes vs Time for bearing at 5000rpm, 5kg load with 0.5mm defect on inner ring.

Fig 7.36c: Amplitudes vs Time for bearing at 5000rpm, 5kg load with 1.0mm defect on inner ring.
In the time domain analysis it is summarized that, for variation in rpm with 1mm defect size, the amplitudes of vibration for outer ring defected bearing are more than inner ring defected bearing. Hence, defect on outer ring is more severe than defect on inner ring.

7.4 Summary

The comparison of theoretical, numerical and experimental results at various speeds and loads with various defect sizes on outer ring and inner ring of the bearing has been made. These comparisons are shown in Fig 7.37 to Fig 7.40. It is clearly observed that, for constant defect size when speed increases, amplitude increases with square of multiple of speed. Thus when speed is increased by five times, the amplitude of vibration is 25 times the initial value of amplitude of vibration. At the same time, for constant speed, the amplitudes of vibration are directly proportional to size of defect. Amplitudes of vibration for various speeds and defect sizes are plotted and tabulated in Table 7.2.

For outer ring defected bearings, an average variation of 9% in amplitudes of vibrations is observed in theoretical and experimental values at speed range of 1000 to 5000 rpm. Whereas an average variation of 8% in amplitudes of vibration is observed in numerical and experimental values for the same speed range.

For inner ring defected bearings, an average variation of 11% in amplitudes of vibrations at speed range of 1000 rpm to 5000 rpm is observed in theoretical and experimental values. Whereas an average variation of 10% in amplitudes of vibrations
for the same speed range is observed in numerical and experimental values. It is also
noted that the theoretical, numerical and experimental results for 1mm defect size at
any speed and load are coinciding.

From Fig 7.37a and b, it is noted that outer ring defected bearings give amplitudes of
vibration in the range of 10 to 60 mm/s², whereas inner ring defected bearings give
amplitudes of vibration in the range of 7 to 40 mm/s².

Similar trend is obtained at 2000 rpm and as shown in Fig 7.38a and b. The
amplitudes of vibrations are in the range of 40 to 250 mm/s² for outer ring defected
bearings and 25 to 150 mm/s² for inner ring defected bearings.

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**Fig 7.37a:** Comparison of Vibration amplitudes at 1000rpm for various defect sizes on Outer ring.

**Fig 7.37b:** Comparison of Vibration amplitudes at 1000rpm for various defect sizes on inner ring.

**Fig 7.38a:** Comparison of Vibration amplitudes at 2000rpm for various defect sizes on Outer ring.

**Fig 7.38b:** Comparison of Vibration amplitudes at 2000rpm for various defect sizes on inner ring.
From Fig 7.39a and b it is observed that amplitudes of vibration increase with speed and defect size. Here at 3000rpm, the amplitudes of vibration are 100 to 600 mm/s$^2$ and 50 to 325 mm/s$^2$ for outer ring and inner ring defected bearings respectively. Fig 7.40a and b depicts the theoretical, numerical and experimental amplitudes of vibration with respect to defect sizes on outer ring and on inner ring bearing at 5000 rpm. It is obvious that, for the defected outer ring bearing, the vibration of amplitude is in the range of 224 to 1840 where as for inner defected bearing it is in the range of 196 to 1093 mm/s$^2$.

In all the three approaches, a good agreement is observed for both outer ring and inner ring defected bearings.

As discussed in earlier paragraphs, outer ring is fixed in the housing and inner ring is rotating with shaft speed. Hence defect is stationary in case of outer ring defected bearings and it is always placed at maximum position in the load zone.
Vibration amplitudes go on decreasing when defect is deviating from maximum position in load zone and theoretically amplitudes becomes zero outside the load zone. But experimentally it always shows some non zero amplitudes even outside the load zone because at higher speed it always senses the vibration from other sources of the system. In case of FEM also, some non zero amplitudes are observed outside the load zone because FEM is also numerical approximation method and it is very difficult to model and mesh the complicated components such as bearings. Even the results obtained by FEM in the present work are closer to calculated and measured values. Fig 7.41 depicts acceleration versus defect position for test bearing with 1mm defect on outer ring at 5000rpm.

![Graph showing acceleration versus defect position for test bearing with 1mm defect on outer ring at 5000rpm](image)

The results obtained in sections 7.1, 7.2 and 7.3 has significant effect on amplitudes of vibration and frequency with variations in speed and defect size. It is summarized that, for any speed and defect size, the outer ring defected bearing gives better response in terms of peaks and characterized defect frequencies in comparison with inner ring defected bearings. The reason is that in prior case, the defect unaltered its position with the rotation and remained in the load zone at maximum position and hence no variations in amplitude of vibration is noted where as in second case, defect is rotating with the shaft from maximum to minimum position and vice versa in the load zone and therefore the variation in amplitudes of vibration is noticed. Table 7.1 depicts the characteristics of defect frequencies at different speeds. The values of amplitudes of vibration of outer ring defected bearings and inner ring defected bearings at various conditions are as shown in Table 7.2.
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Table 7.1: Defect frequencies at different speeds.

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Table 7.2: An overall review of Theoretical, Numerical and Experimental values of amplitudes of vibrations at different speeds and defect sizes. 154